

# Physics at the Tevatron

## Lecture III

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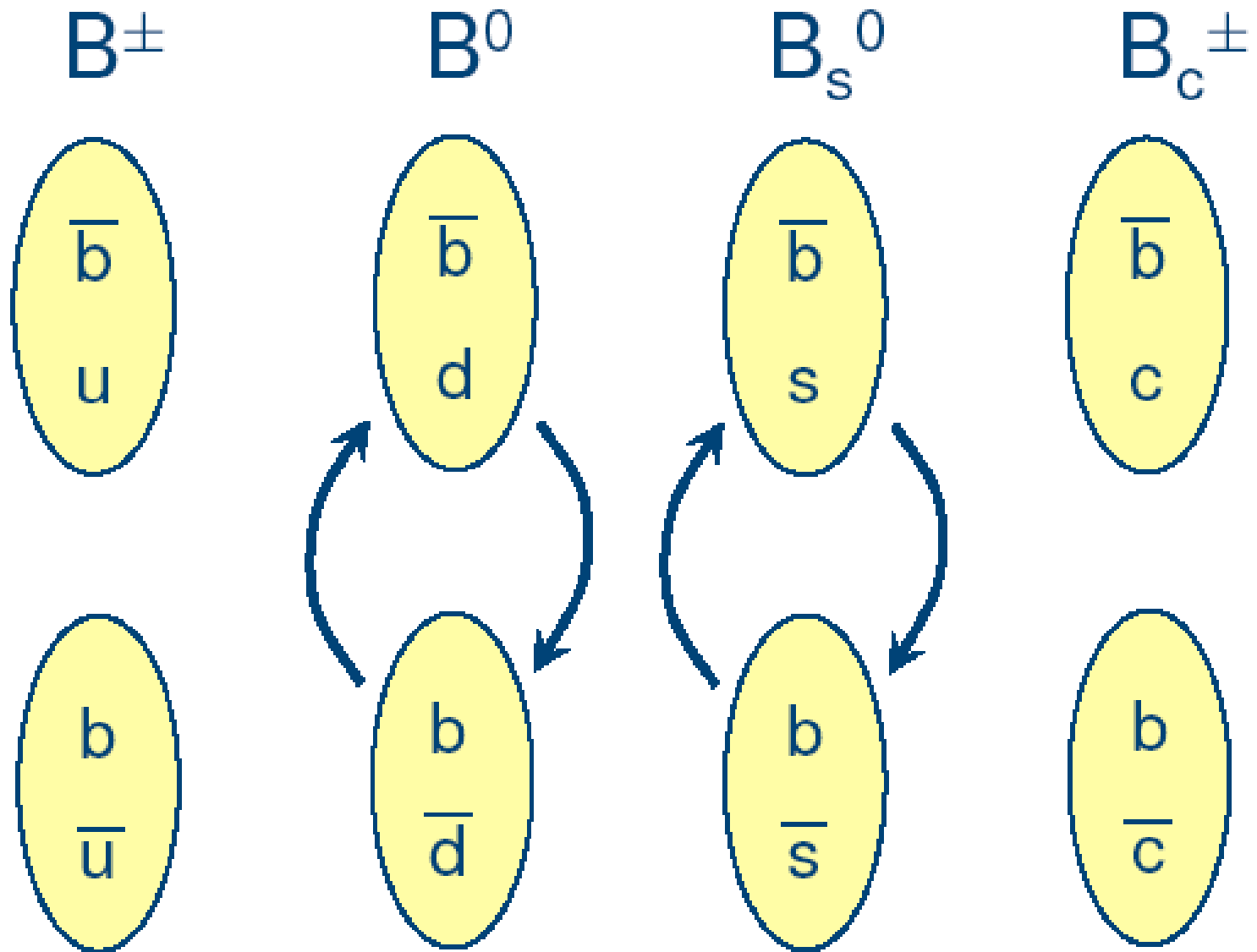
CERN, May 15-19th 2006

# Outline

- Lecture I:
  - The Tevatron, CDF and DØ
  - Production Cross Section Measurements
- Lecture II:
  - Top Quark Mass and the Higgs Boson
    - jet energy scale and b-tagging
- Lecture III
  - $B_s$  mixing and  $B_s \rightarrow \mu\mu$  rare decay
    - Vertex resolution and particle identification
- Lecture IV
  - Supersymmetry and High Mass Dilepton/Diphoton
    - Missing ET

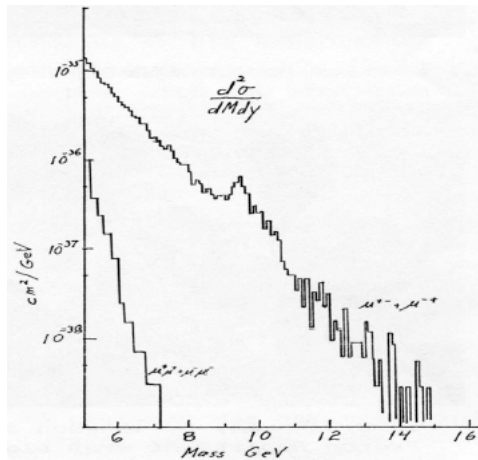
# B mesons

Anti-Matter Matter



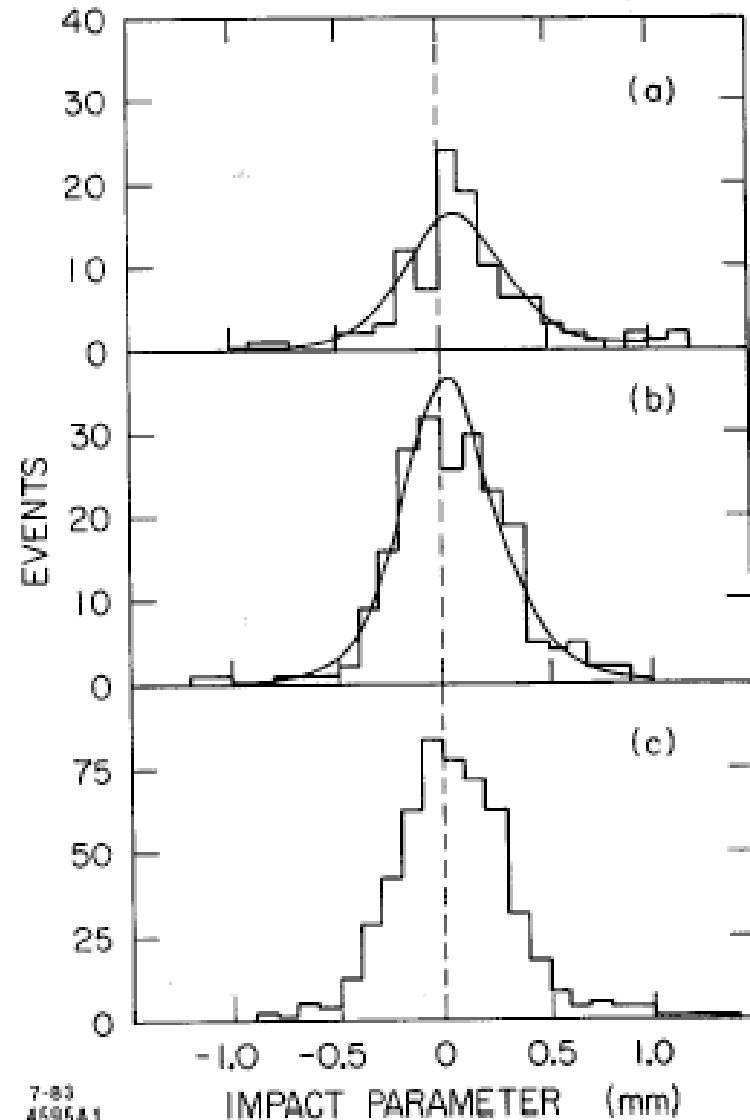
# History: B Mass and Lifetime

- Upsilon observation 1978
  - 3rd generation exists
  - Mass about 5 GeV



- Lifetime observation 1983:
  - Lifetime =  $1.5 \text{ ps}^{-1}$
  - Enables experimental techniques to identify B's

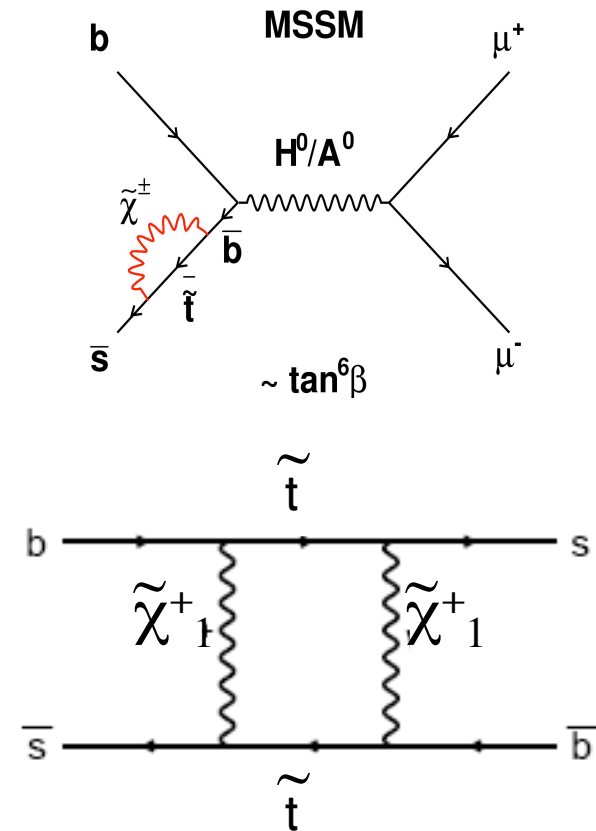
Phys.Rev.Lett.51:1316,1983



7-83  
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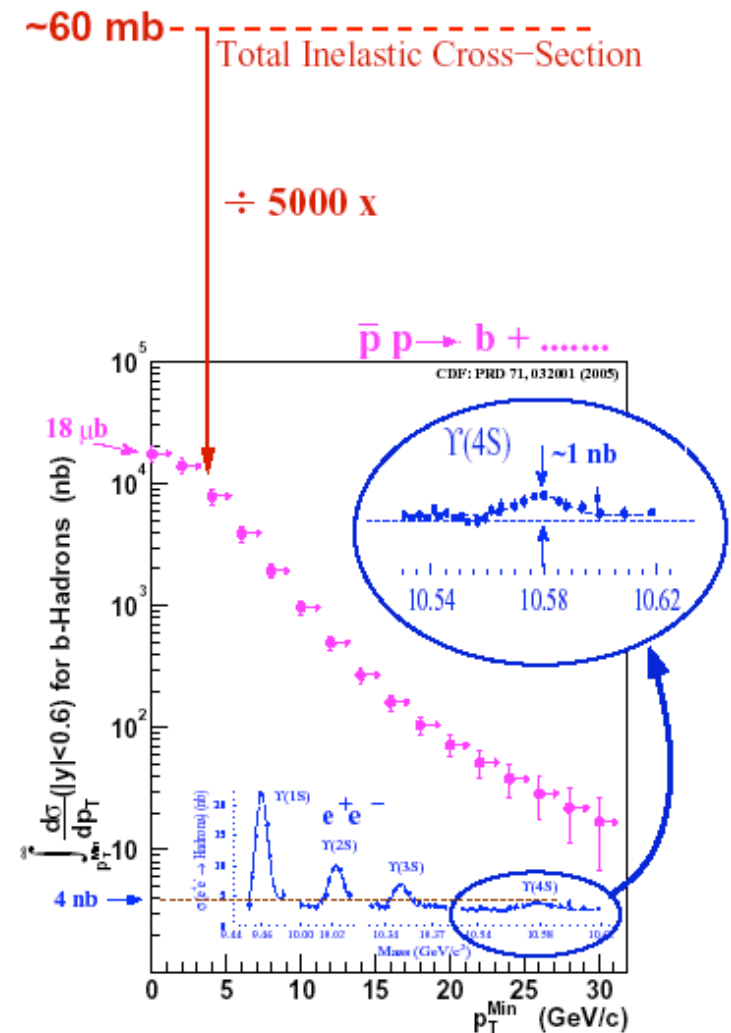
# Why B Physics?

- New physics could contribute to B-decays
  - SUSY particles can contribute in addition to SM particles
  - $Z'$  bosons could also alter the effective couplings
- Complementary to direct searches

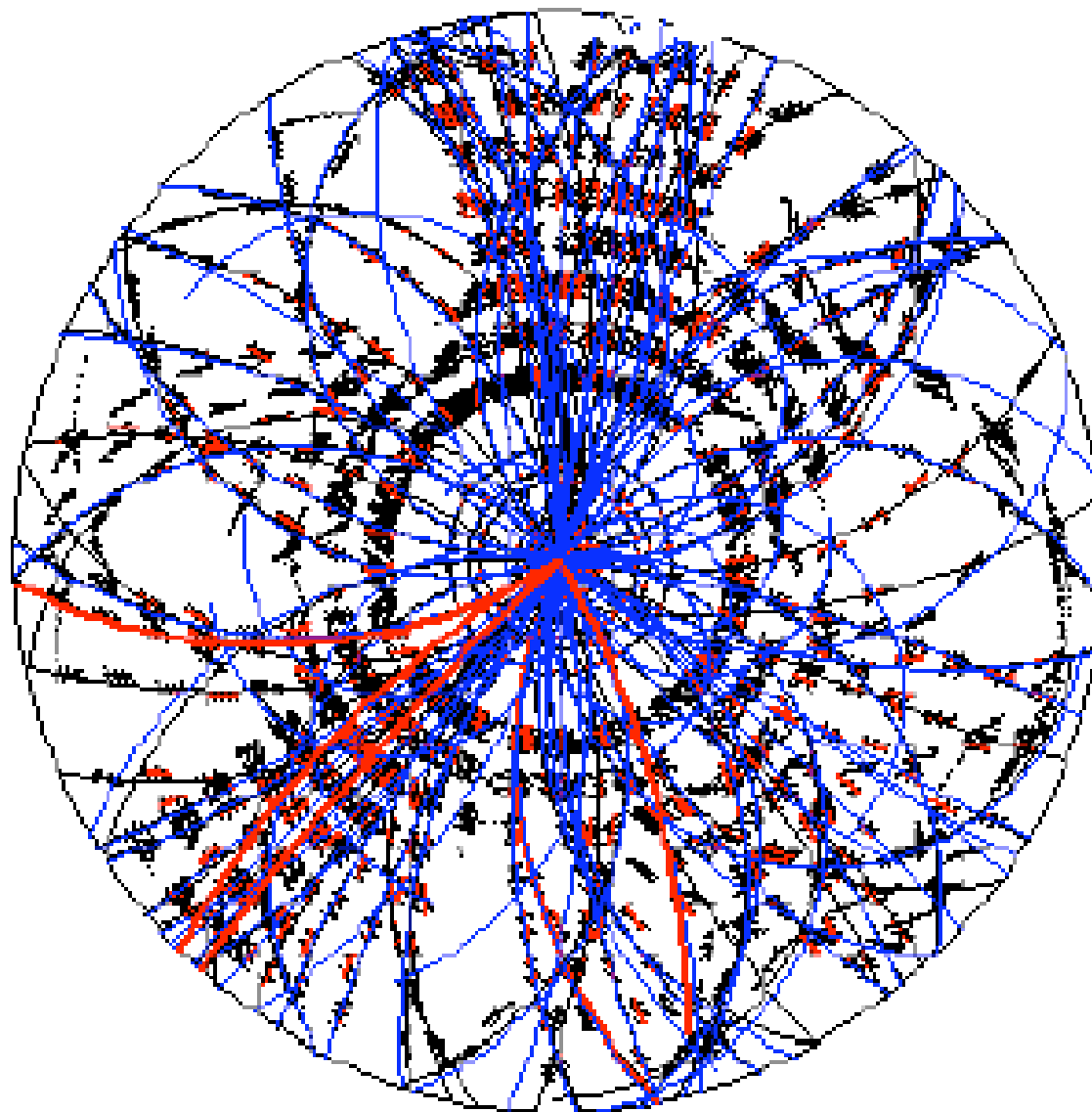


# B Physics at Hadron Colliders

- Pro's
  - Large cross section:  $18 \mu\text{b}$ 
    - 1000 times larger than at B-factories
  - Produce all B-hadron species:
    - $B^0$ ,  $B_s^0$ ,  $\Lambda_b$ ,  $B_c$ , ...
- Con's
  - No reconstruction of neutrals (photons,  $\pi^0$ 's)
  - difficult to trigger, bandwidth restrictions
  - Messy environment

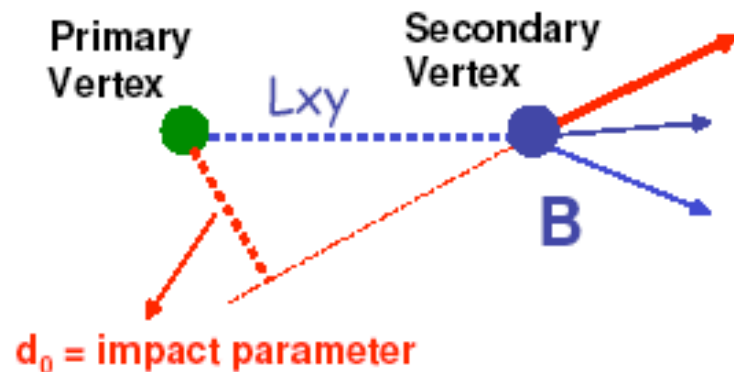


# A typical B-decay event

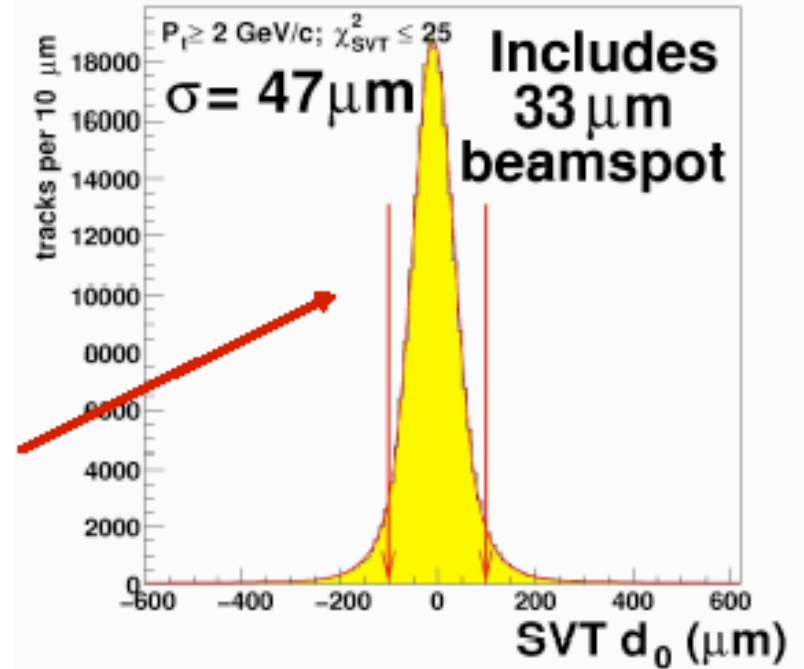


# The SVT Trigger at CDF

- trigger  $B_s \rightarrow D_s^- \pi$ ,  $B_s \rightarrow D_s^- l^+$



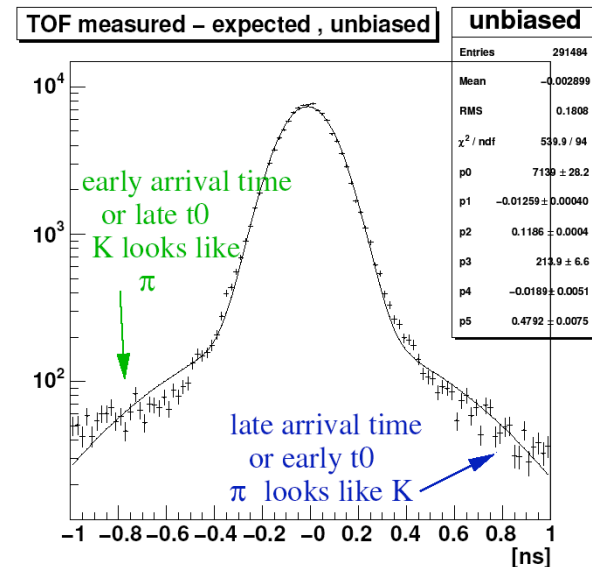
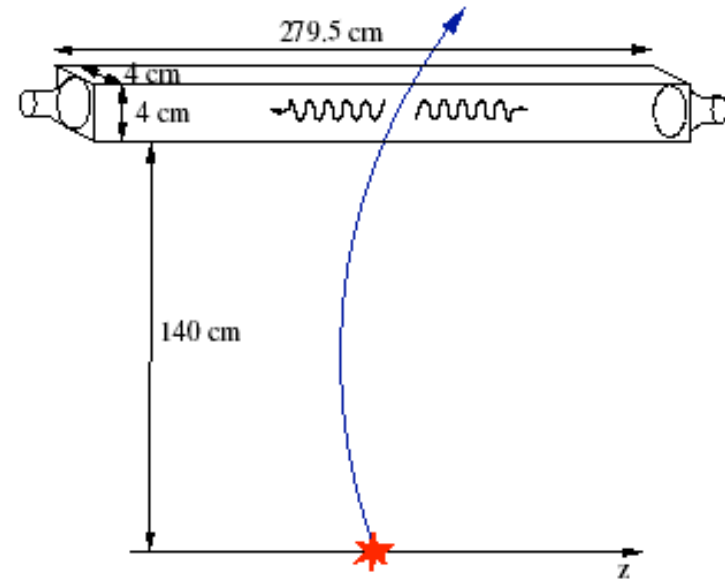
- trigger extracts 20 TB /sec
- “unusual” trigger requirement:
  - two displaced tracks:  
( $p_T > 2 \text{ GeV}/c$ ,  $120 \mu\text{m} < |d_0| < 1 \text{ mm}$ )
- requires precision tracking in SVX





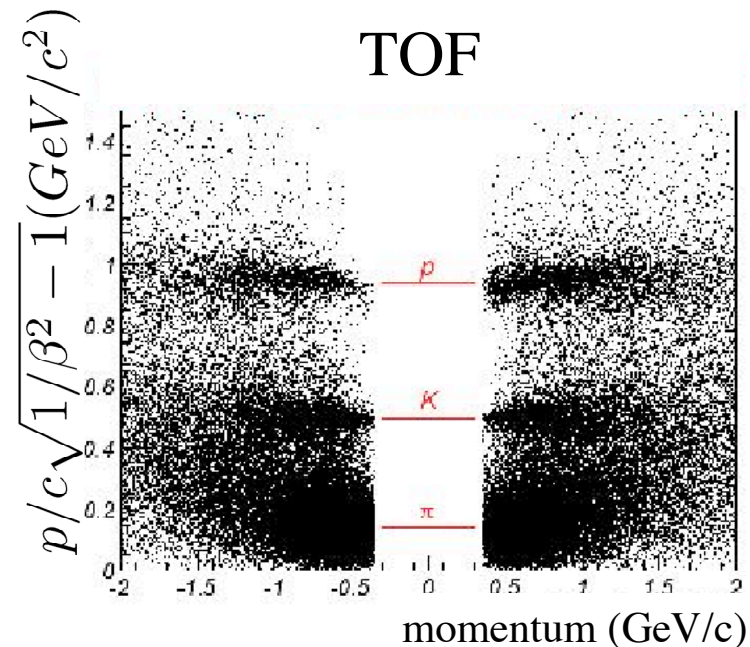
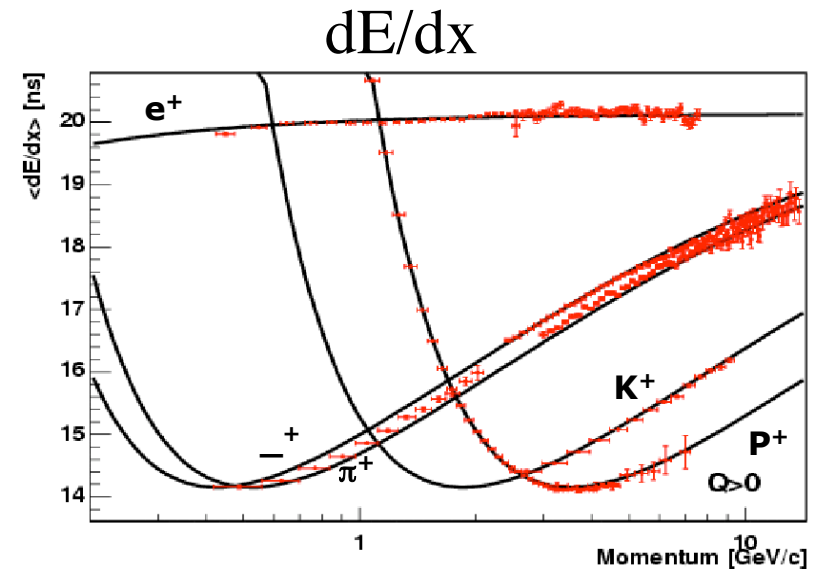
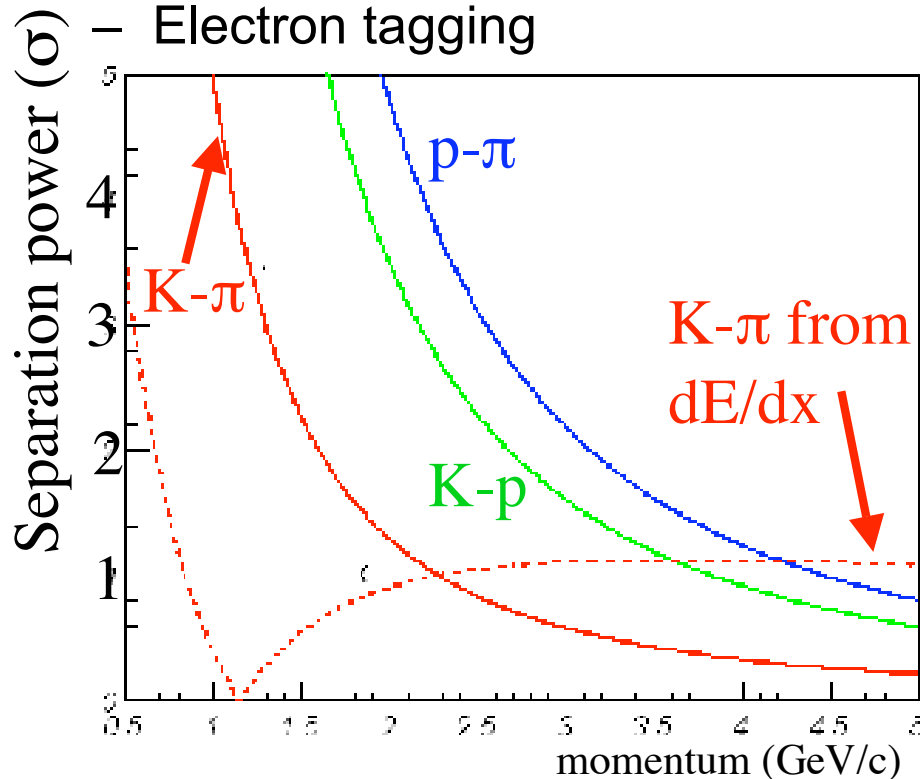
# Particle Identification

- TOF detector measures time of arrival in at  $r=140\text{cm}$ 
  - Resolution 119 ps
  - Time depends on particle mass:
    - For  $M>0$ :  $v \neq c$
- Measure pulse height in COT,  $dE/dx$ :
  - Ionization depends on particle species



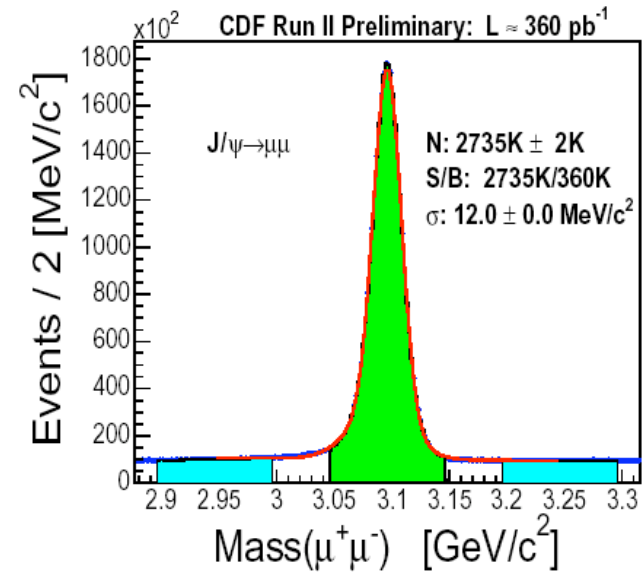
# Particle Identification Results

- Separate kaons from pions
  - $dE/dx$  gives  $1\sigma$  separation for  $p > 2$  GeV
  - TOF gives better separation at low  $p$
- Used for:
  - Kaon/pion separation
  - Electron tagging

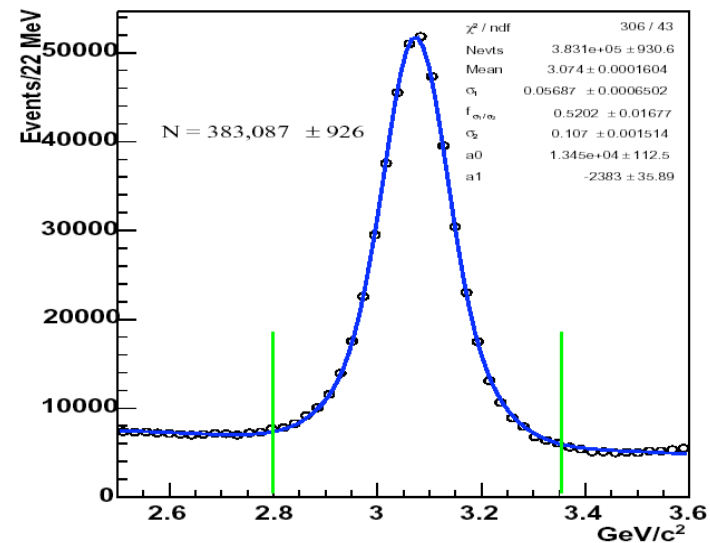


# J/Psi signals

- Superb calibration signal
- Yields:
  - CDF 2.7M / 360 pb<sup>-1</sup>
  - DØ: 0.4M / 250 pb<sup>-1</sup>
- Mass resolution ~1%
  - CDF: 12 MeV
  - DØ: 60 MeV
- Used to calibrate:
  - Magnetic field
  - Detector material
  - Momentum resolution
  - Hadron calorimeter



J/ψ Invariant Mass

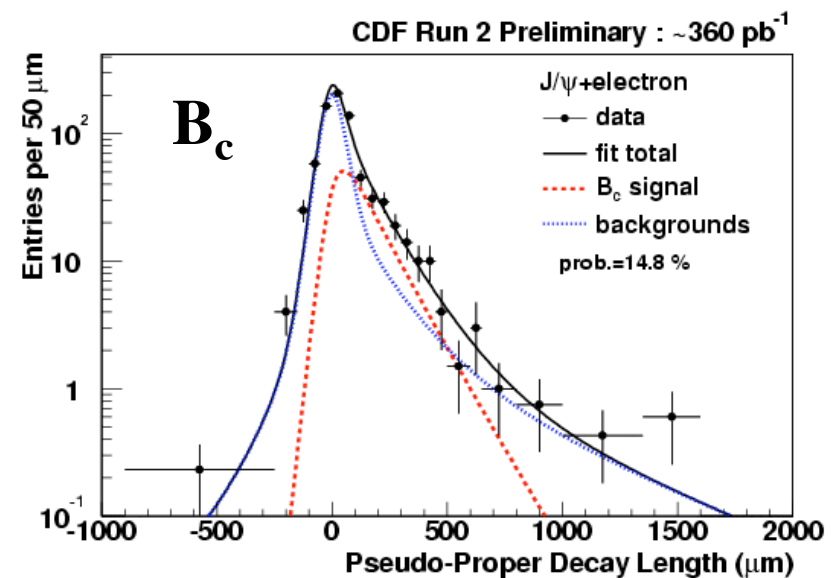
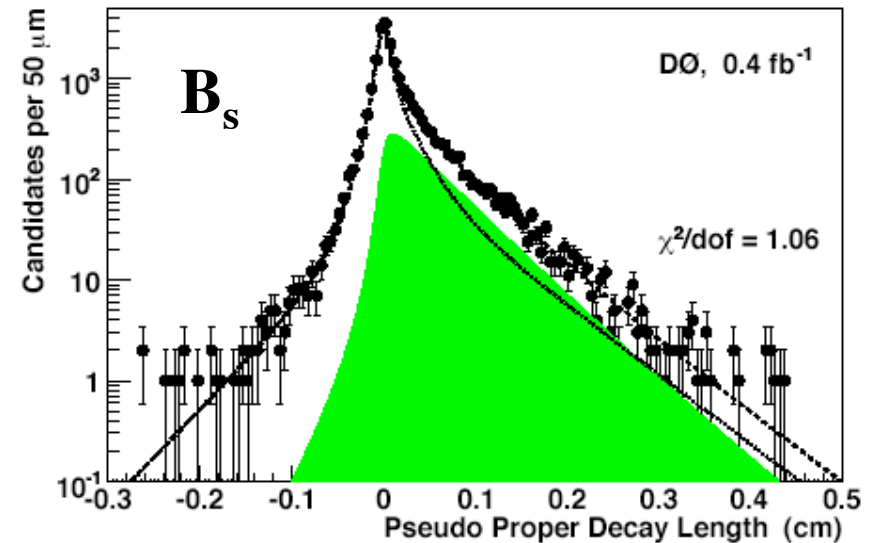


# Lifetime Measurements: $B_s^0, \Lambda_b, B_c$

- Measure lifetimes of many B hadrons:

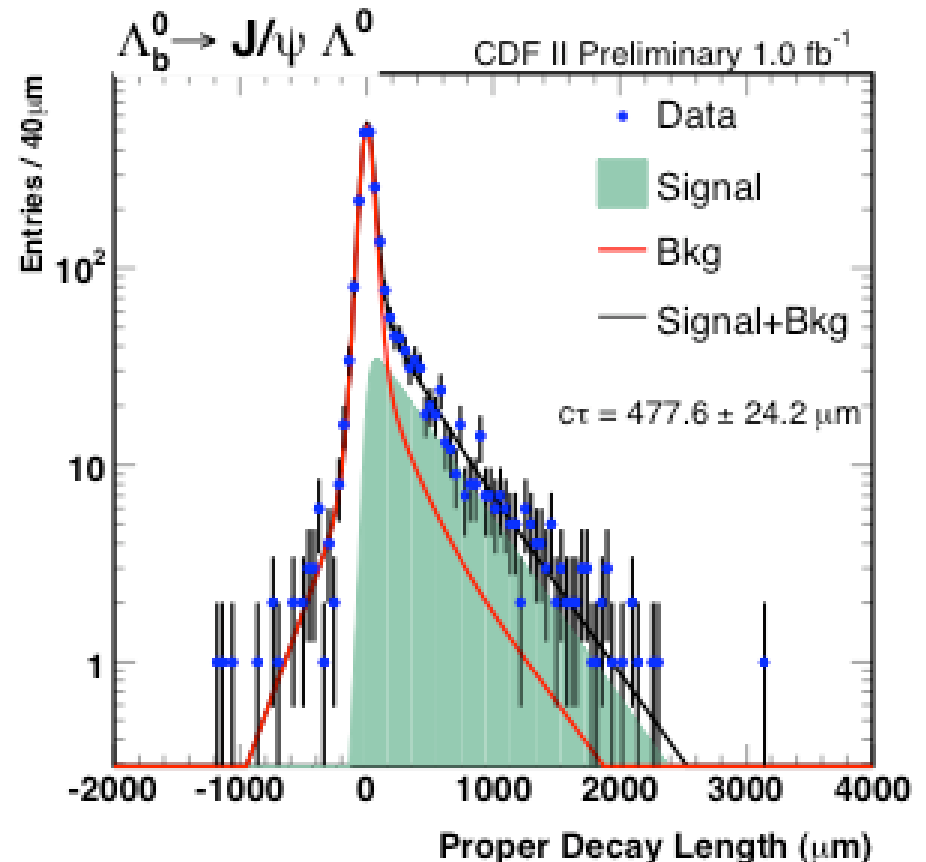
$$\lambda_B = \frac{L_{xy}}{(\beta\gamma)_T^B} = L_{xy} \frac{cM_B}{p_T}$$

- Why?
  - Tests theoretical predictions:
    - Electroweak and strong sector play role
  - Demonstrates understanding of vertex resolution/detector
    - Important for both low and high  $P_T$  physics programme



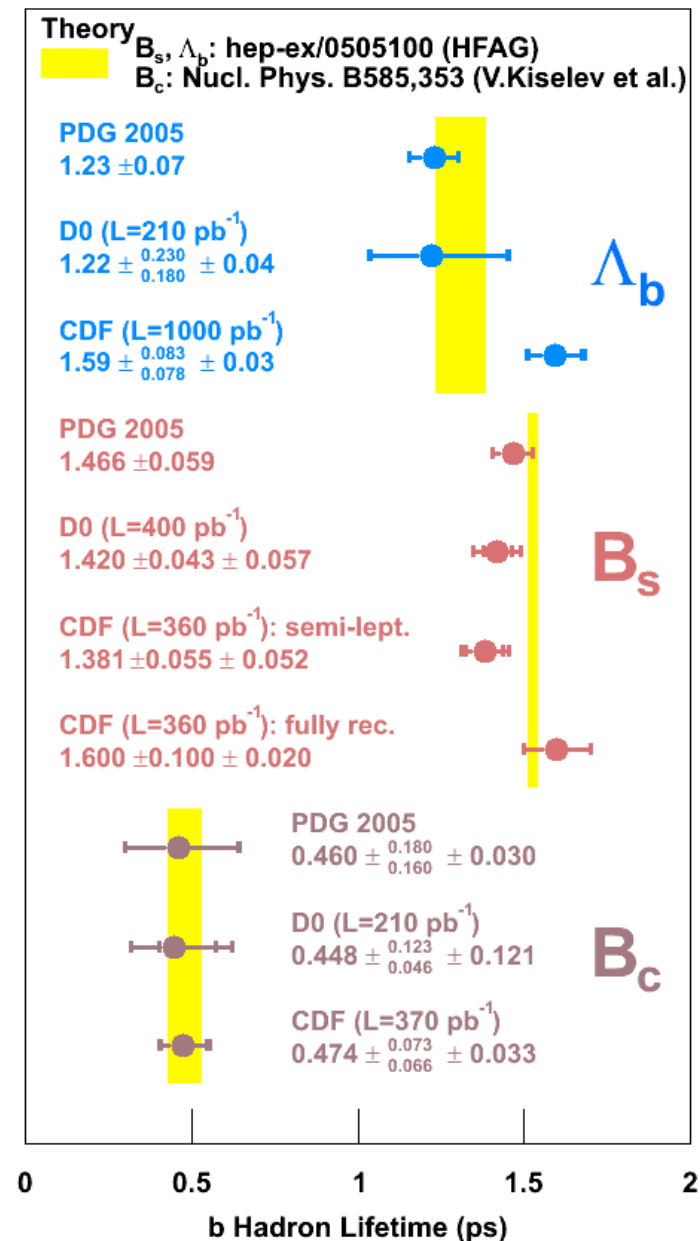
# $\Lambda_b$ Lifetime

- Standing puzzle at LEP
  - Why is the lifetime so much shorter than that of the other B mesons
  - Measurements were mostly made in semileptonic decays due to low stats
- New at Tevatron
  - Measurements in fully hadronic decay modes
  - Indication it may be higher in those modes
- Are we missing anything in semileptonic decays
  - Other than the neutrino???



# Summary of Lifetimes

- Good agreement with PDG world average
  - Mostly LEP data
  - Precision similar
- Theoretical predictions mostly confirmed
- Outstanding questions
  - Is  $B_s$  lifetime really shorter than  $B_d$  lifetime?
  - Is  $\Lambda_b$  lifetime really shorter?
  - Are the semileptonic measurements systematically lower than the hadronic ones?
- Will be answered with increasing data samples



# $B_s$ mixing

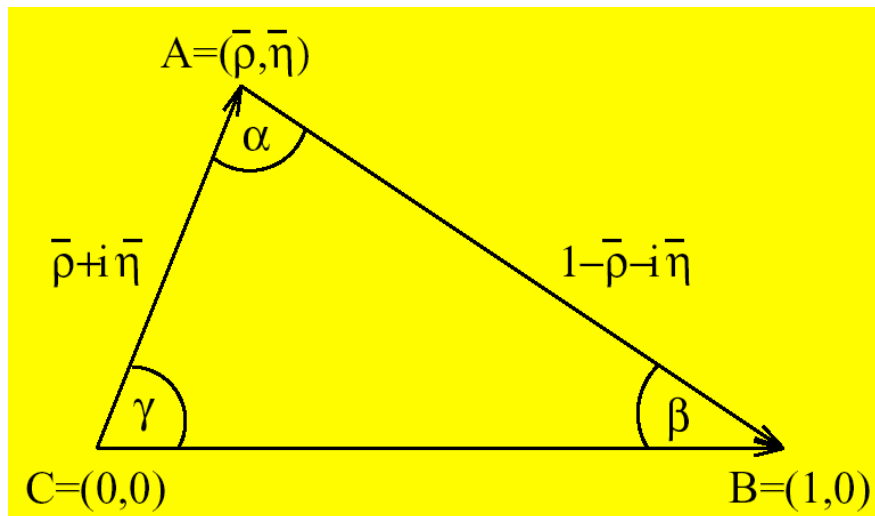
# Cabibbo-Kobayashi-Maskawa Matrix

CKM Matrix

Wolfenstein parameterization

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

$$V_{ts} \sim \lambda^2, \quad V_{td} \sim \lambda^3, \quad \lambda = 0.224 \pm 0.012$$



- Is this 3x3 matrix unitary?
  - 4th generation quarks?
  - New forces? E.g. SUSY?
- Measure each side and each angle:
  - Do all measurements cross at one point?



# B Mixing

- Neutral B Meson system

$$|B\rangle = (\bar{b}s); |\bar{B}\rangle = (b\bar{s})$$

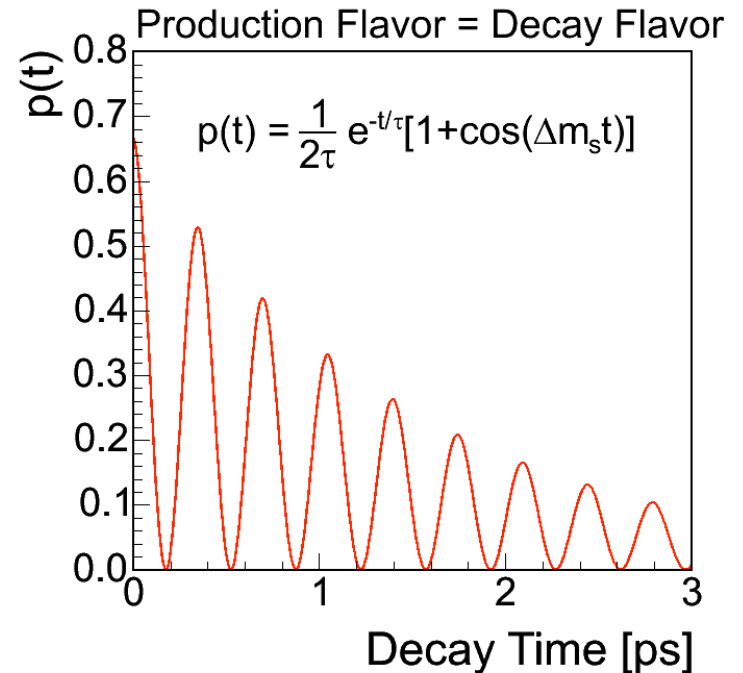
- Mass eigenstates are mixture of CP eigenstates:

$$|B_L\rangle = p|B^0\rangle + q|\bar{B}^0\rangle$$

$$|B_H\rangle = p|B^0\rangle - q|\bar{B}^0\rangle$$

$$\text{with } |p|^2 + |q|^2 = 1$$

- $B_H$  and  $B_L$  may have different mass and lifetime
  - $\Delta m = M_H - M_L$   
( $>0$  by definition)
  - $\Delta\Gamma = \Gamma_H - \Gamma_L$  where  $\Gamma = 1/\tau$

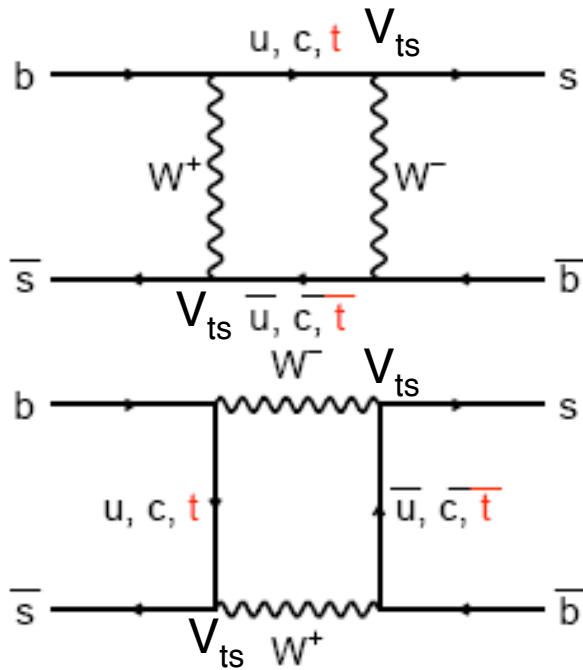


- The case of  $\Delta\Gamma = 0$

$$p(B \rightarrow B) = \frac{e^{-t/\tau}}{2\tau} (1 + \cos \Delta m t)$$

$$p(B \rightarrow \bar{B}) = \frac{e^{-t/\tau}}{2\tau} (1 - \cos \Delta m t)$$

# B<sub>s</sub> mixing and the CKM Matrix

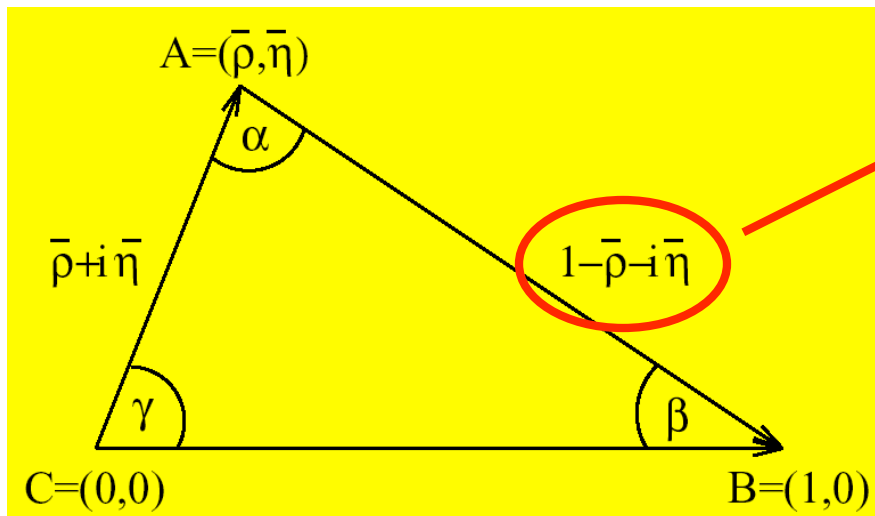


Ratio of frequencies for B<sup>0</sup> and B<sub>s</sub>

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \frac{f_{B_s}^2 B_{B_s}}{f_{B_d}^2 B_{B_d}} \frac{|V_{ts}|^2}{|V_{td}|^2} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}$$

$\xi = 1.210^{+0.047}_{-0.035}$  from lattice QCD  
(hep-lat-0510113)

$$V_{ts} \sim \lambda^2, \quad V_{td} \sim \lambda^3, \quad \lambda = 0.224 \pm 0.012$$



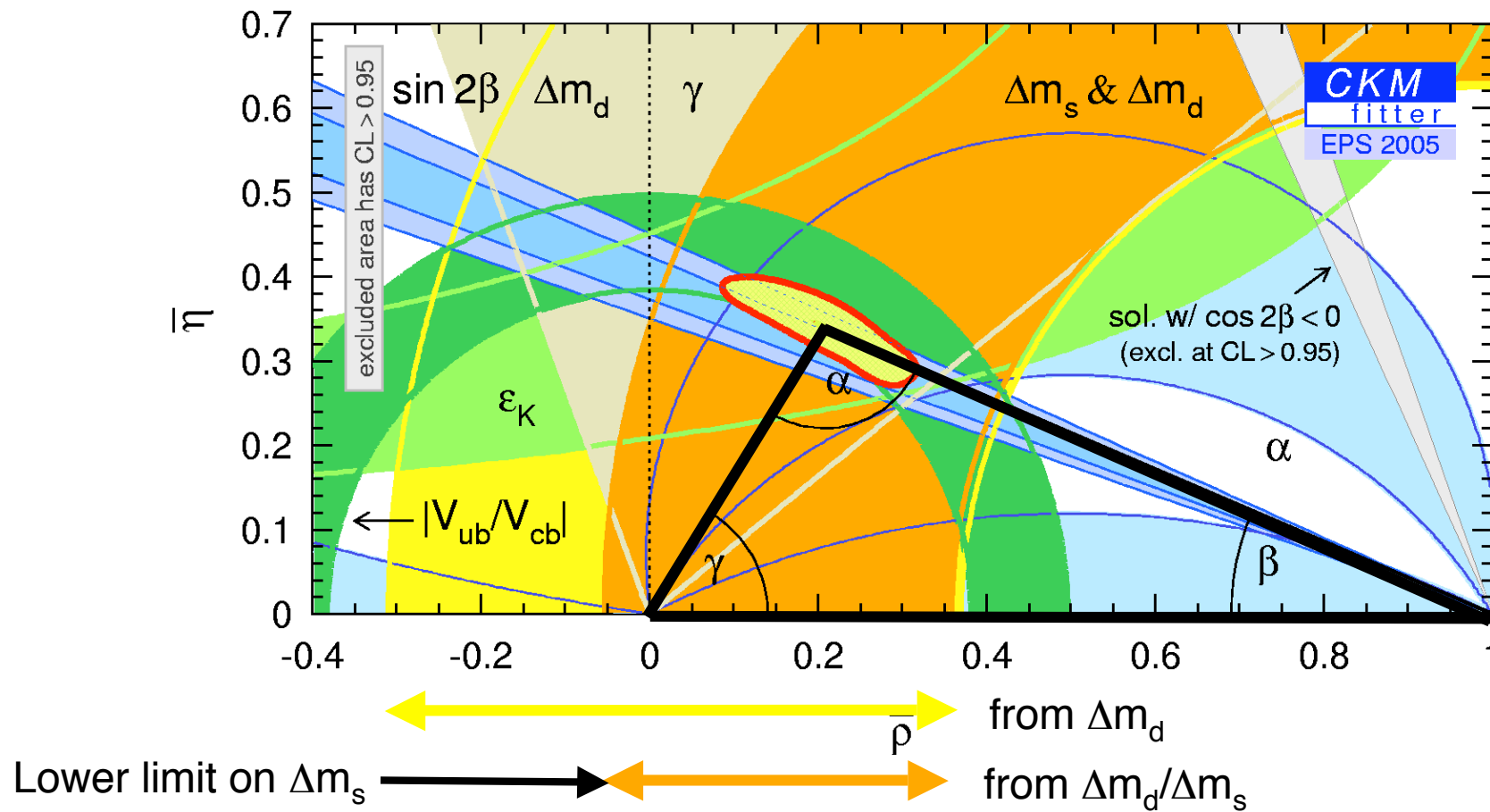
Constrain side of triangle:

$$|V_{td}|^2 = A^2 \lambda^4 [(1-\rho)^2 + \eta^2]$$

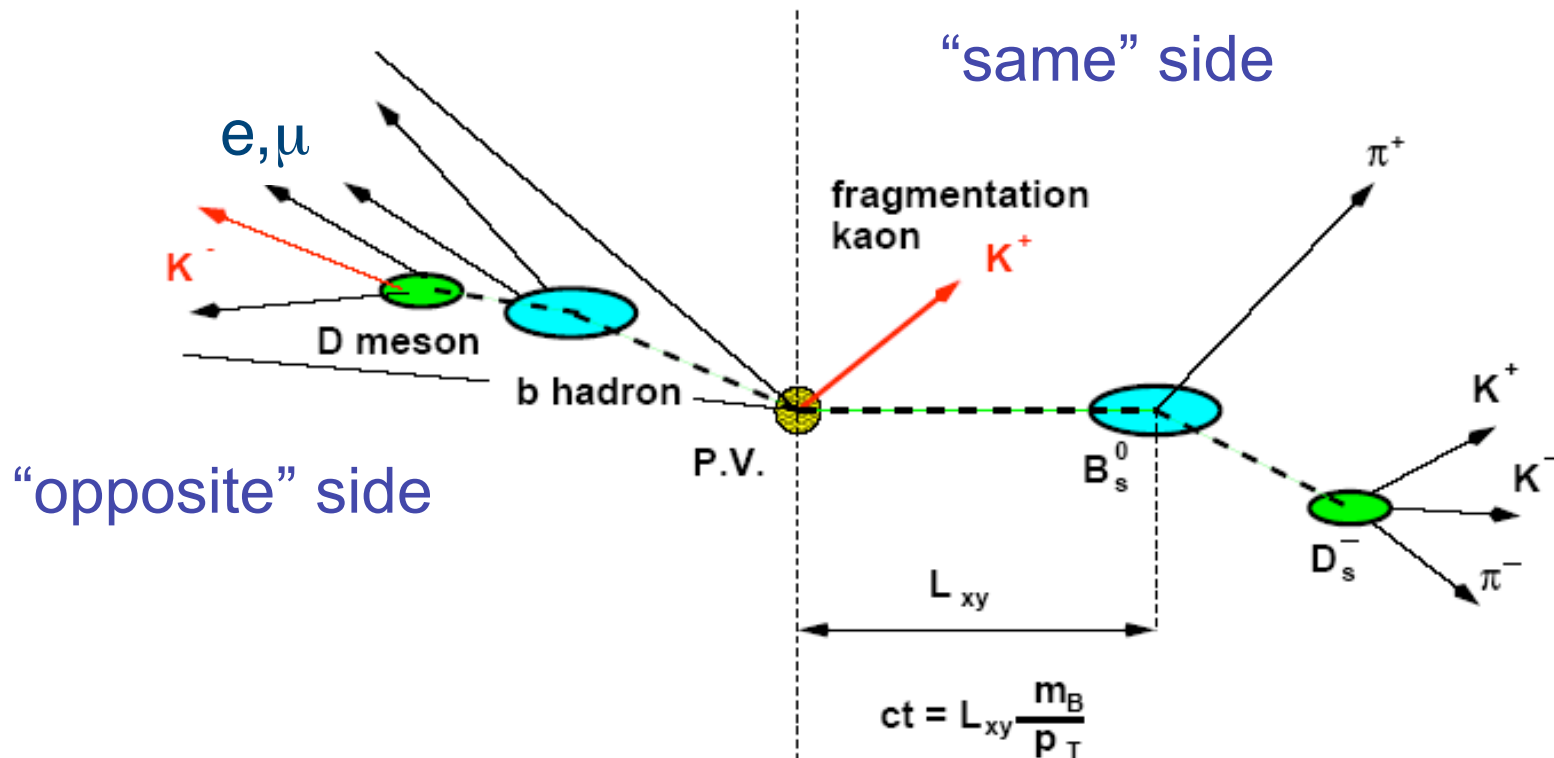
$$\frac{|V_{td}|^2}{|V_{ts}|^2} = (1-\rho)^2 + \eta^2 .$$

# Unitarity Triangle Fit

- just for illustration, other fits exist
- CKM Fit result:  $\Delta m_s: 18.3^{+6.5}_{-1.5} (1\sigma) : ^{+11.4}_{-2.7} (2\sigma) \text{ ps}^{-1}$



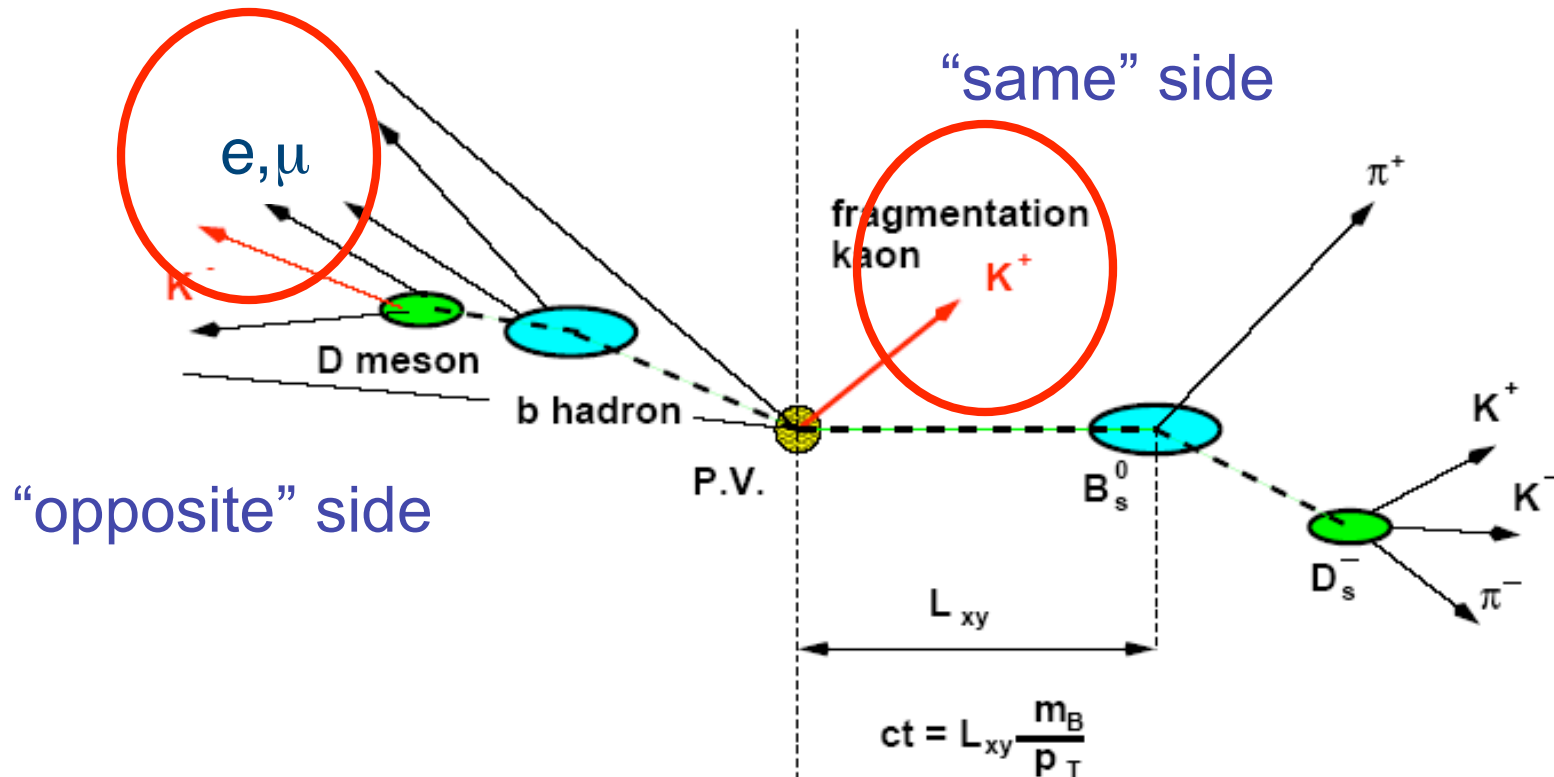
# The “Big” Picture



significance of measurement

$$\frac{1}{\sigma} = \sqrt{\frac{S\epsilon D^2}{2}} e^{-\frac{(\Delta m_s \sigma_t)^2}{2}} \sqrt{\frac{S}{S+B}}$$

# Flavour tagging



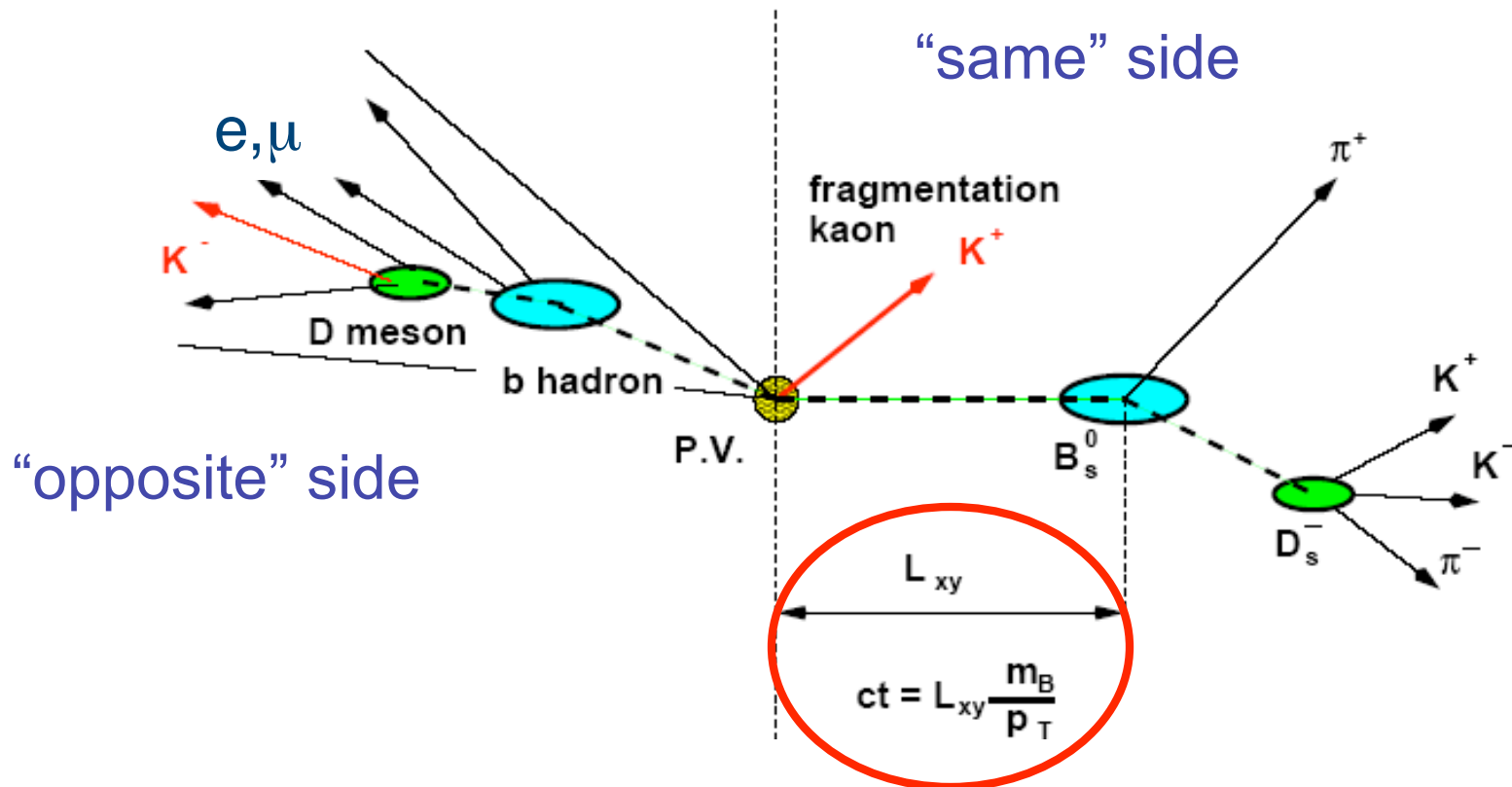
Time resolution

$$\frac{1}{\sigma} = \sqrt{\frac{S\epsilon D^2}{2}} e^{-\frac{(\Delta m_s \sigma_t)^2}{2}} \sqrt{\frac{S}{S+B}}$$

Flavour tagging

B signal efficiency

# Time resolution

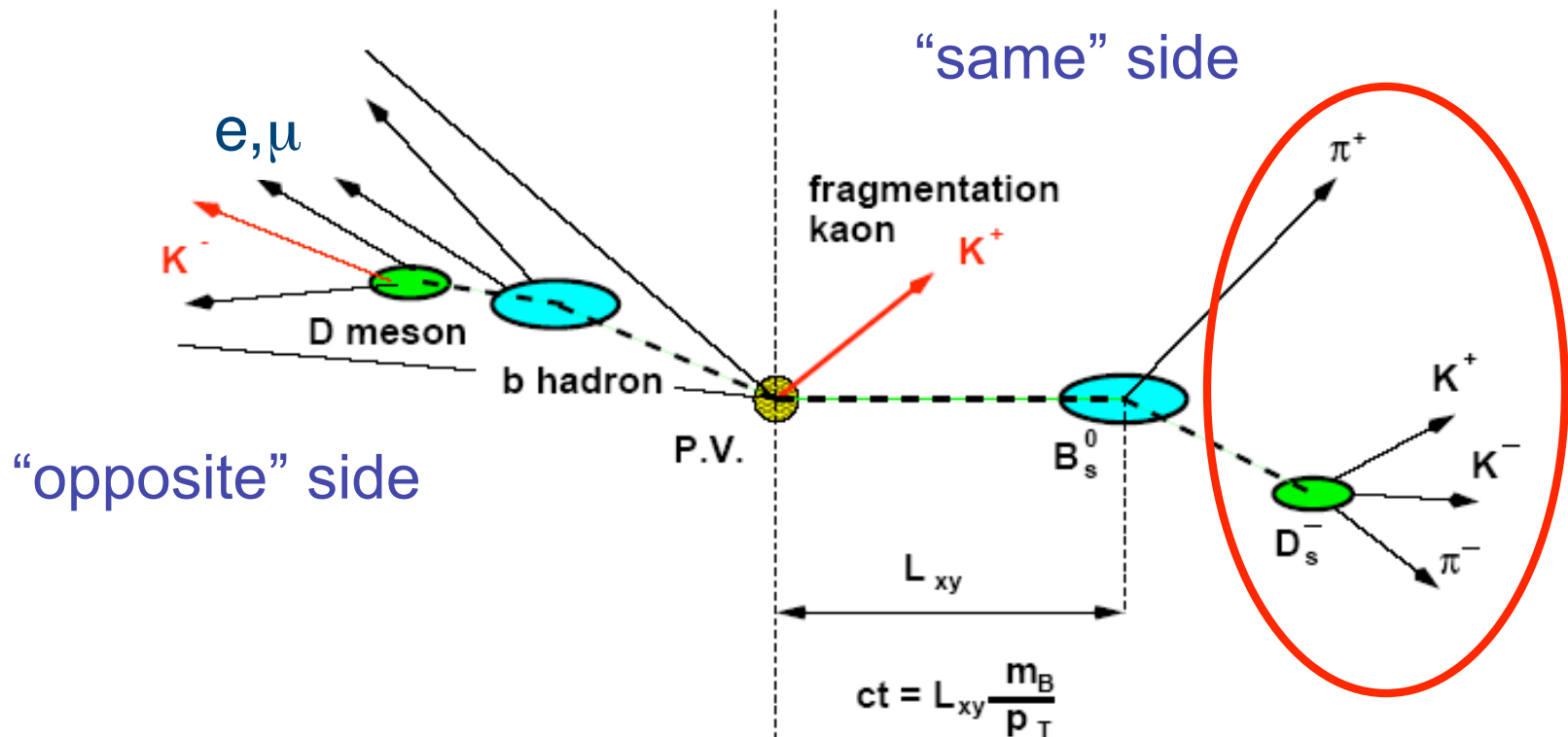


$$\frac{1}{\sigma} = \sqrt{\frac{S\epsilon D^2}{2}} e^{-\frac{(\Delta m_s \sigma_t)^2}{2}} \sqrt{\frac{S}{S+B}}$$

Time resolution

B signal efficiency

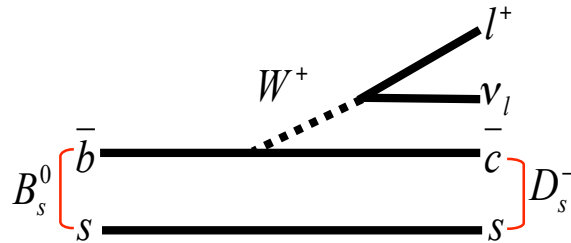
# Signal Identification



$$\frac{1}{\sigma} = \sqrt{\frac{S\epsilon D^2}{2}} e^{-\frac{(\Delta m_s \sigma_t)^2}{2}} \sqrt{\frac{S}{S+B}}$$

B signal reconstruction

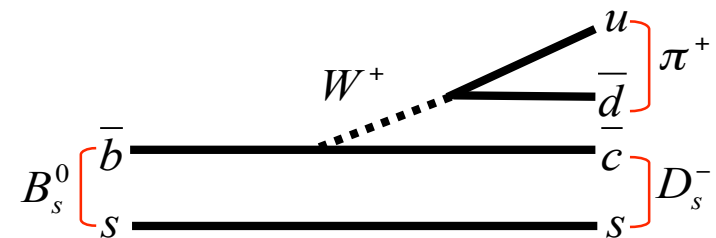
# Semileptonic vs Hadronic Decays



- Semileptonic:
  - High statistics:
    - 50K events
  - B momentum not known
    - Neutrino missing
    - Requires average correction factor K

$$ct = L_{xy} \frac{m(B)}{p_T(B)} = L_{xy} \frac{m(B)}{p_T(\ell D)} \cdot K$$

- Poorer time resolution



- Hadronic:
  - Lower statistics:
    - 4K events
  - Full reconstruction of B momentum

$$ct = L_{xy} \frac{m(B)}{p_T(B)}$$

- Excellent time resolution

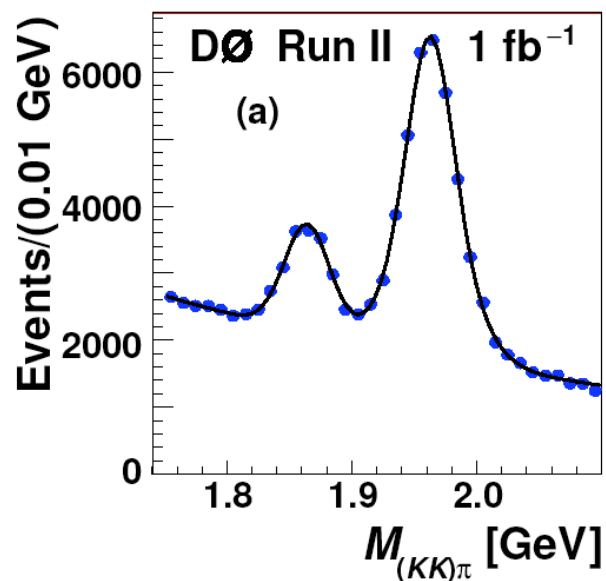
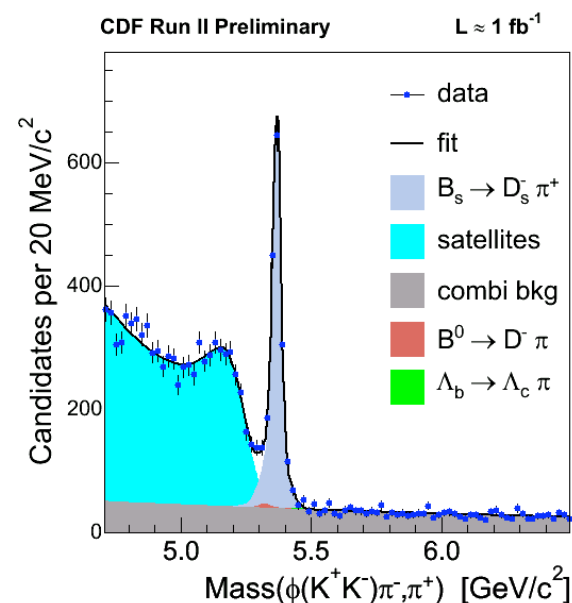
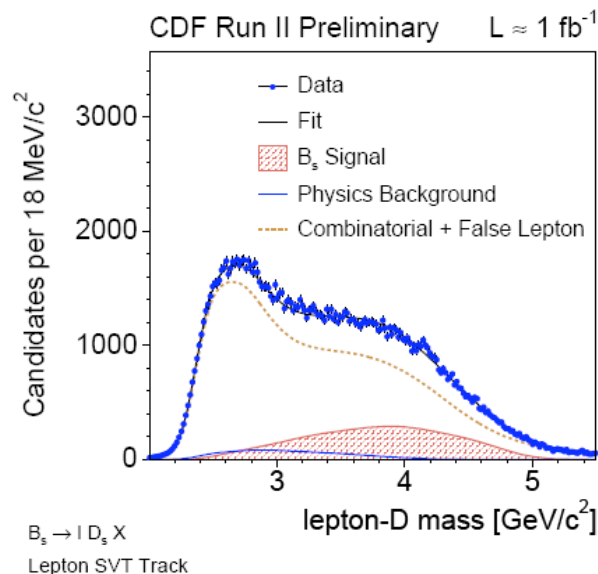
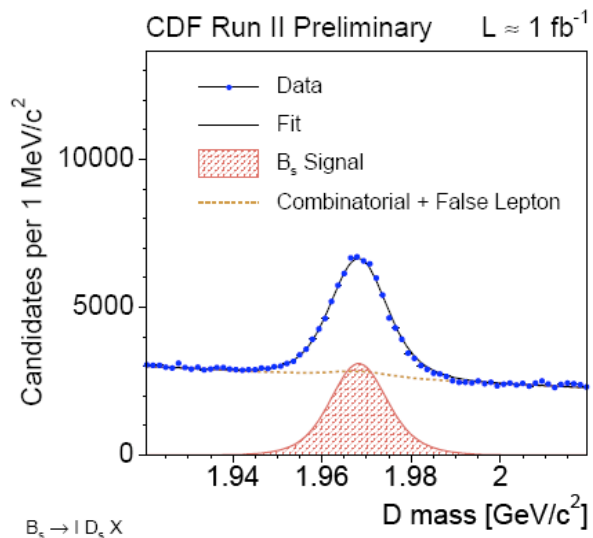
$$\sigma(ct) = \sqrt{(\sigma_0(ct))^2 + (ct \cdot \frac{\sigma(p)}{p})^2}$$



# Semileptonic and Hadronic Signals

Semileptonic:  $B_s \rightarrow l \nu D_s$

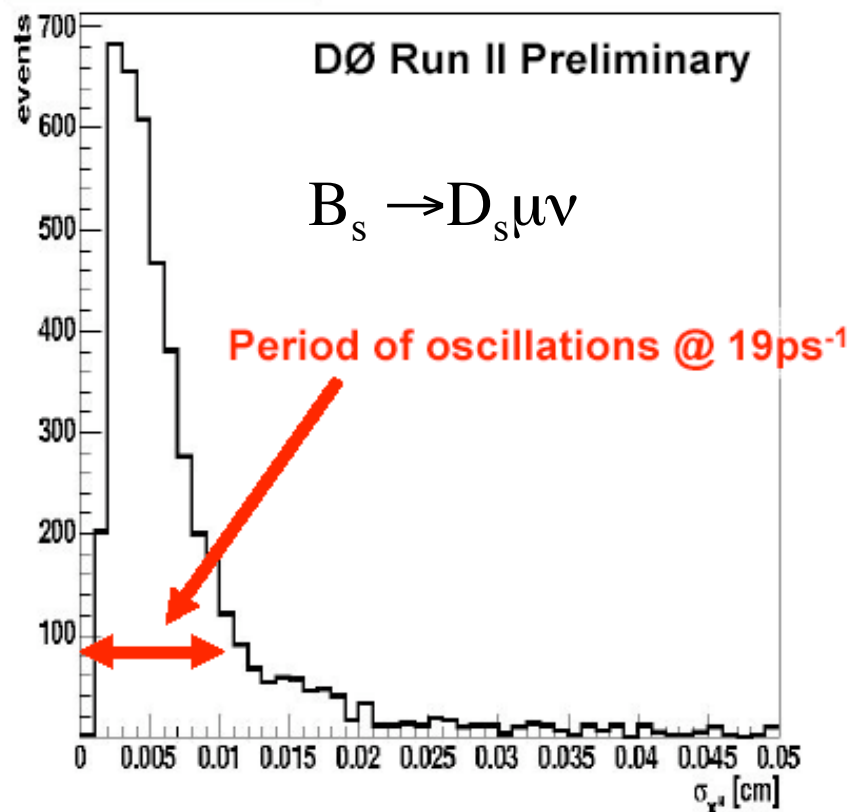
Hadronic:  $B_s \rightarrow \pi D_s$



- Semileptonic decays:
  - DØ:  $\sim 27,000$
  - CDF:  $\sim 53,000$
- Hadronic Decays:
  - CDF:  $\sim 3,700$

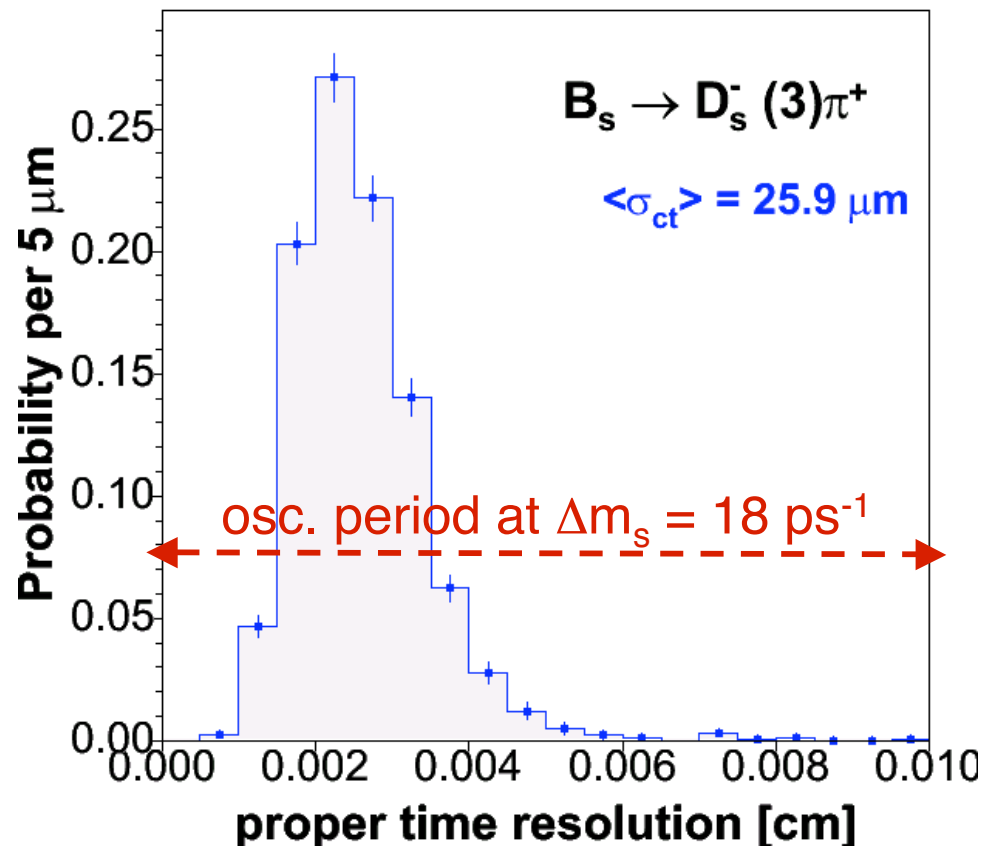
# Proper Time Resolution

VPDL error,  $\mu D_s$  signal



CDF Run II Preliminary

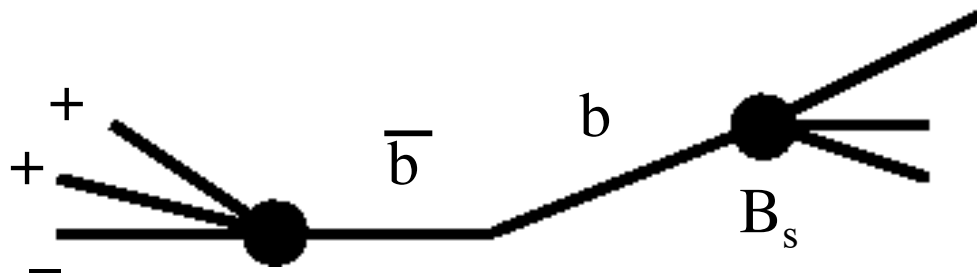
$L = 1.00 \text{ fb}^{-1}$



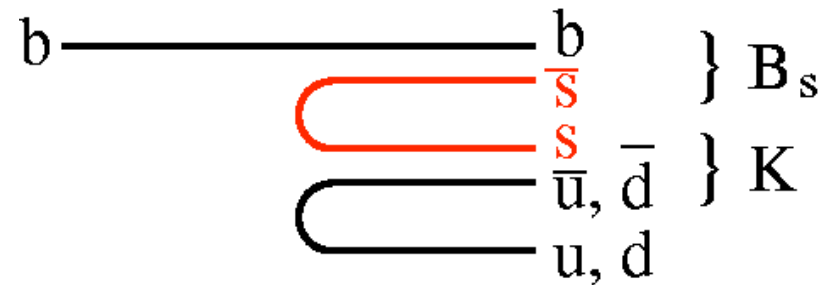
- Semileptonic Decays:
  - Resolution about 1 oscillation period
- Hadronic Decays:
  - Resolution 5 times better than 1 oscillation period

# Production Flavour Tagging

## Opposite side tagging



## Same side tagging

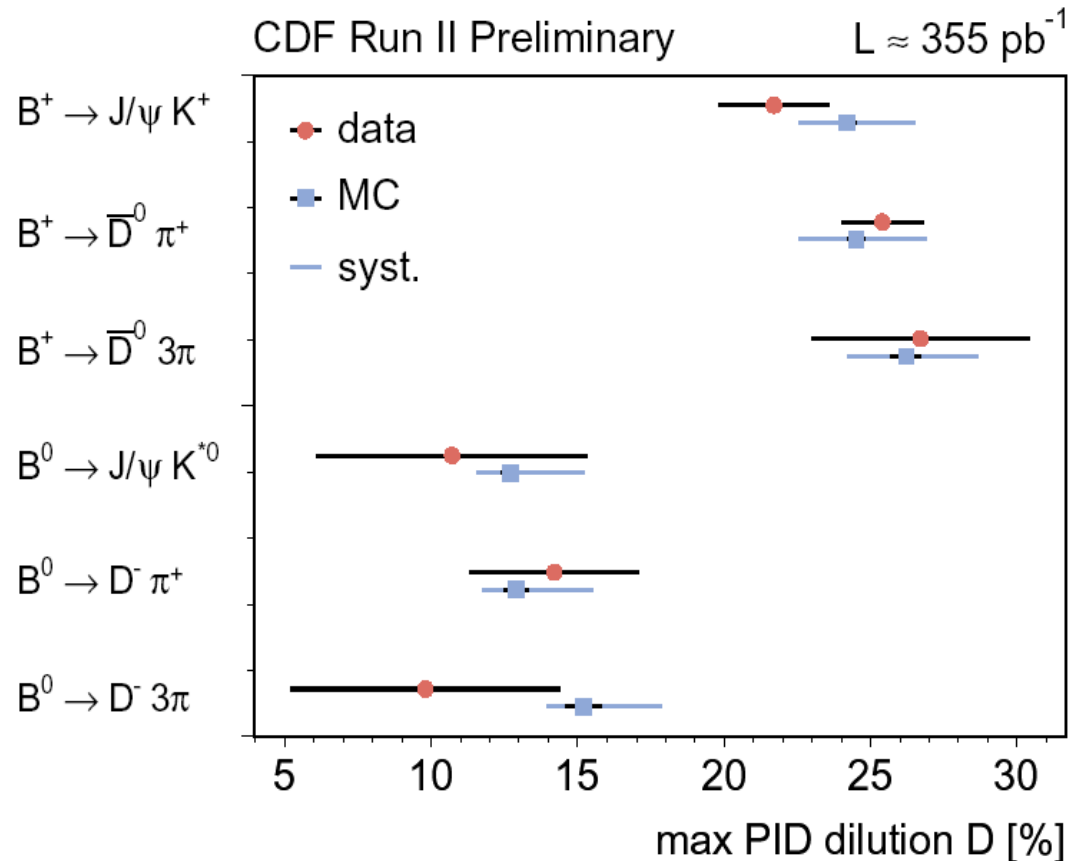


- **Opposite side tags:**
  - Only works for  $b\bar{b}$  production mechanism
  - Used by CDF ( $\epsilon D^2=1.5\%$ ) and DØ ( $\epsilon D^2=2.5\%$ ):
    - Lepton (muon or electron) or jet charge
- **Same side tags:**
  - Identify Kaon from  $B_s$  fragmentation
  - CDF:  $\epsilon D^2=3.5-4.0\%$
- **Figure that matters:  $\epsilon D^2$** 
  - Efficiency  $\epsilon$  of tagging (right or wrong)
  - Dilution  $D$  is fraction of correct tags

$$\epsilon = \frac{N_{tag}}{N_{all}}$$

$$D = \frac{N_{right} - N_{wrong}}{N_{tag}}$$

# Same Side Kaon Tagger Crosschecks

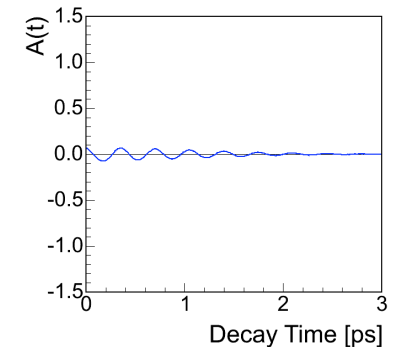


- Have to rely on MC to determine performance of Same Side Kaon Tagger
  - Extensive comparison of data and MC in high statistics B modes
- Good agreement between data and MC => confidence

# “Amplitude Scan”: Measuring $\Delta m_s$

In principle: Measure asymmetry of number of matter and antimatter decays:

$$A(t) \equiv \frac{N(B_s^0 \rightarrow B_s^0)(t) - N(B_s^0 \rightarrow \bar{B}_s^0)(t)}{N(B_s^0 \rightarrow B_s^0)(t) + N(B_s^0 \rightarrow \bar{B}_s^0)(t)} \propto \cos(\Delta m t)$$



In practice: use amplitude scan method

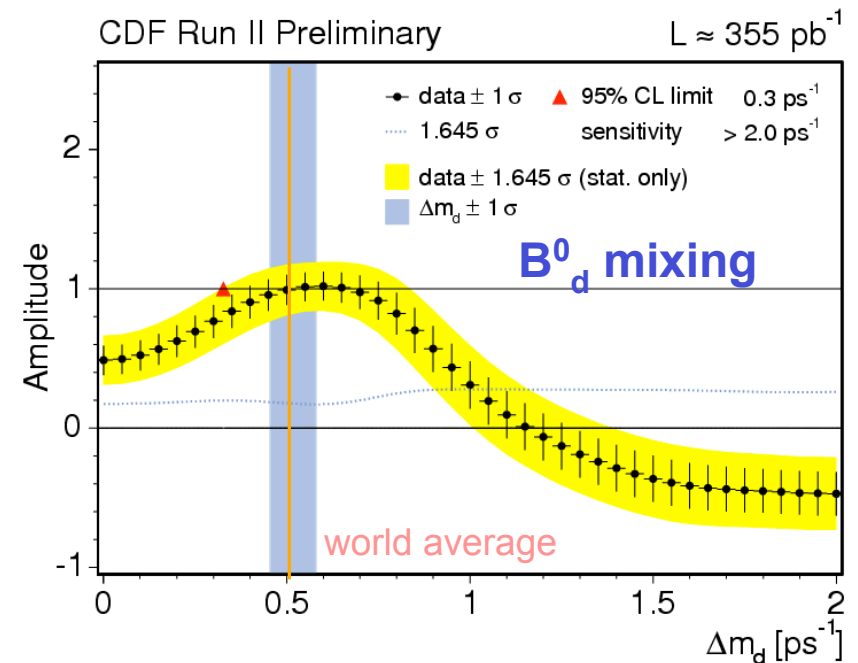
- introduce amplitude to mixing probability formula

$$P_{unmix}^{B_s} = \frac{1}{2} \Gamma_{B_s} e^{-\Gamma_{B_s} t} (1 + A \cos \Delta m_s t)$$

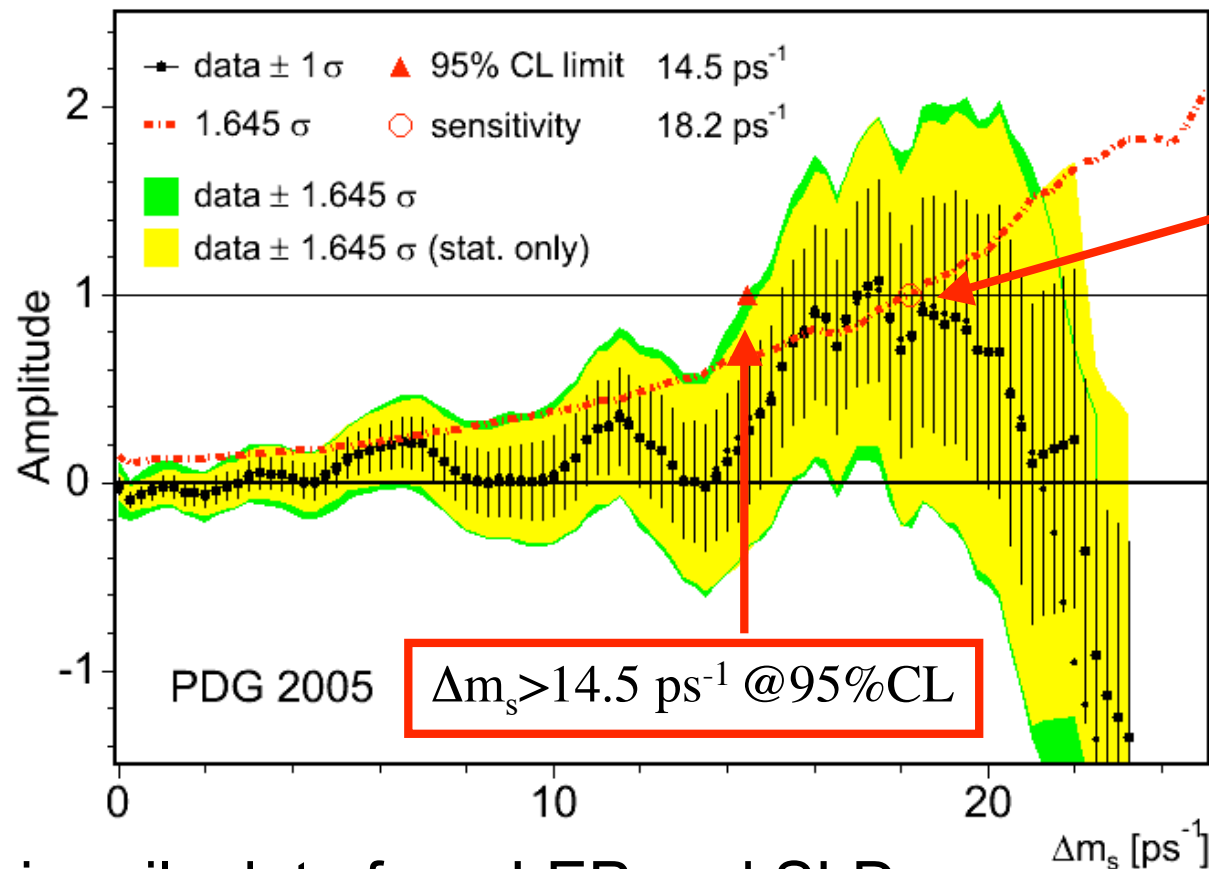
$$P_{mix}^{B_s} = \frac{1}{2} \Gamma_{B_s} e^{-\Gamma_{B_s} t} (1 - A \cos \Delta m_s t)$$

- evaluate at each  $\Delta m$  point
- Amplitude=1 if evaluated at correct  $\Delta m$
- Allows us to set confidence limit when  $1.645\sigma=1$

H. G. Moser, A. Roussarie,  
NIM **A384** (1997)



# The World Data: PDG 2005

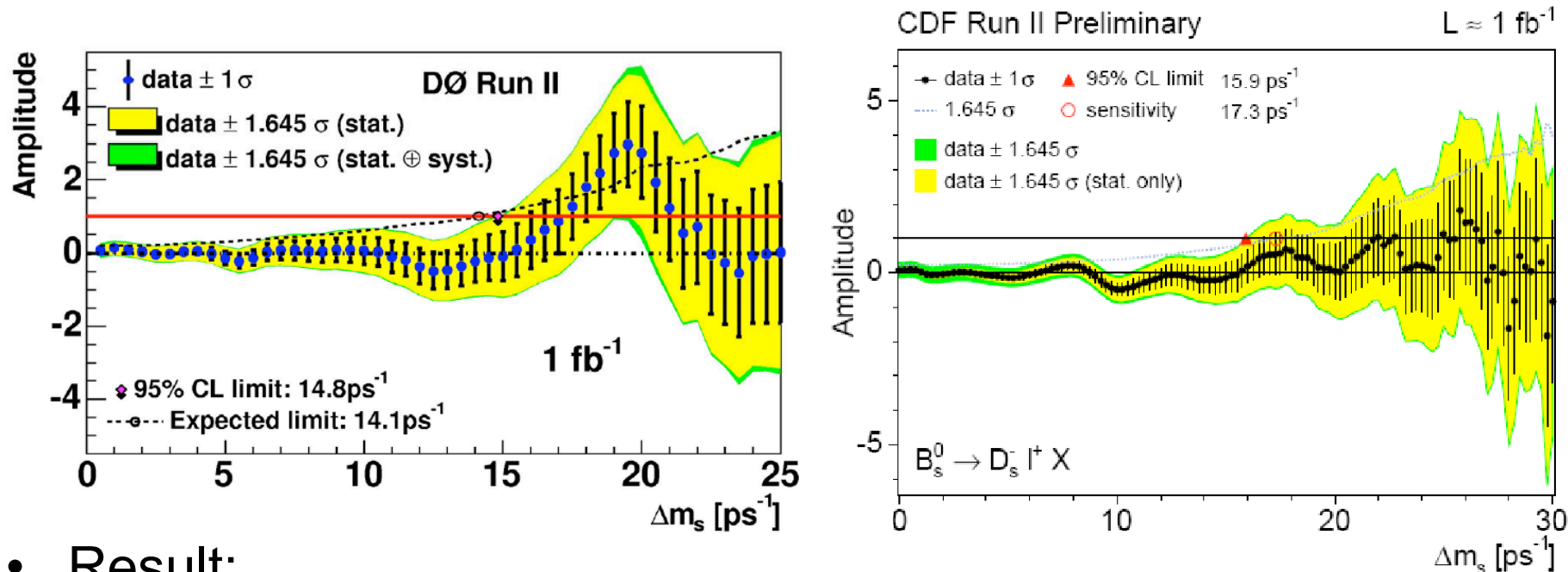


“Sensitivity”:  
expected value  
in absense of  
stat. Fluctuations

⇒ Shows power  
of experiment

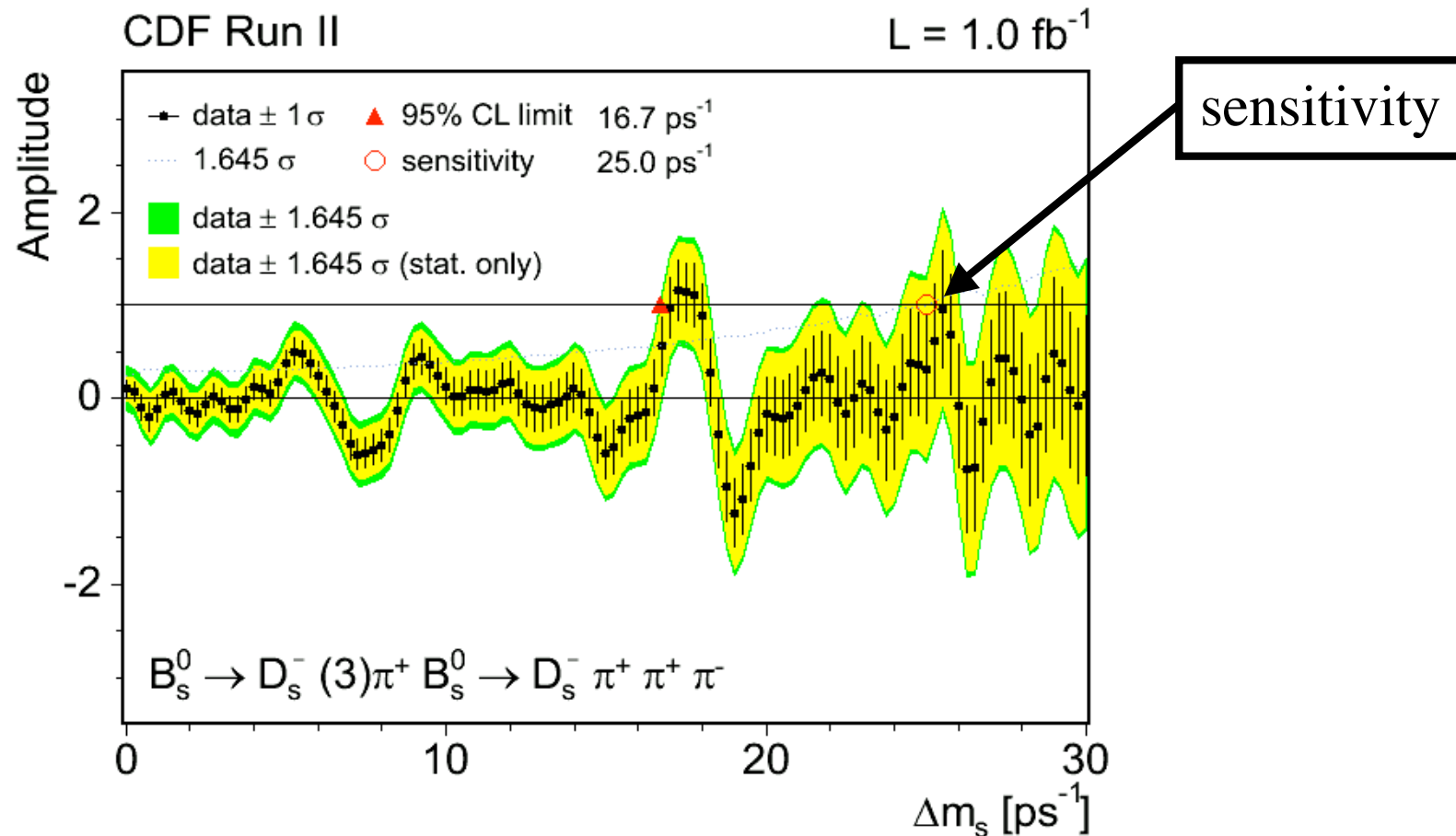
- Primarily data from LEP and SLD:
  - Consistent with no mixing within  $2\sigma$  everywhere
  - Consistent with mixing beyond  $14.5 \text{ ps}^{-1}$ 
    - Actual limit worse than sensitivity
    - either first hint of signal around 17-20 or statistical fluctuation
- Single best experiments sensitivity: ALEPH  $\Delta m_s > 10.9 \text{ ps}^{-1}$

# Amplitude Scan: Semileptonic Decays



- **Result:**
  - DØ see high value at  $19\text{ps}^{-1}$ 
    - $2.5\sigma$  from 0: 1% probability to be consistent with no oscillations
    - $1.6\sigma$  from 1: 10% probability to be consistent with oscillation
  - CDF consistent with both oscillation and no-oscillation hypothesis within  $1\sigma$  for  $\Delta m_s > 15\text{ps}^{-1}$
- Sensitivity similar for CDF and DØ
  - this is *a priori* measure of analysis power
  - DØ:  $14.1\text{ps}^{-1}$ , CDF:  $17.3\text{ps}^{-1}$  (better than best experiment before)

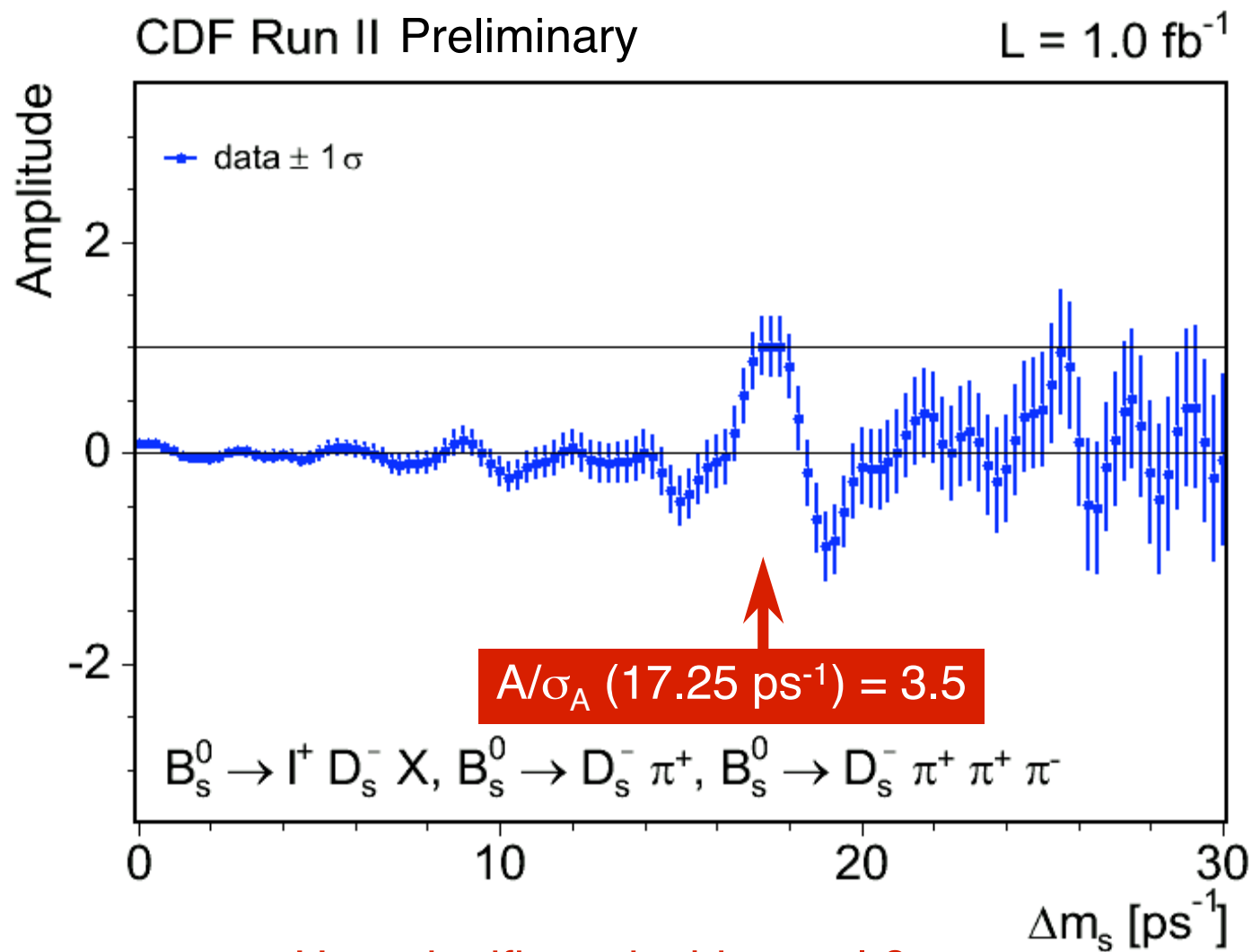
# Amplitude Scan: Hadronic Decays



- CDF sees  $3.5\sigma$  oscillation signal at  $\Delta m_s = 17.3 \text{ ps}^{-1}$ 
  - Consistent with oscillations:  $A=1$
  - Sensitivity:  $25 \text{ ps}^{-1}$  (much better than the entire world data!)
- Use likelihood method to quantify signal and measure  $\Delta m_s$

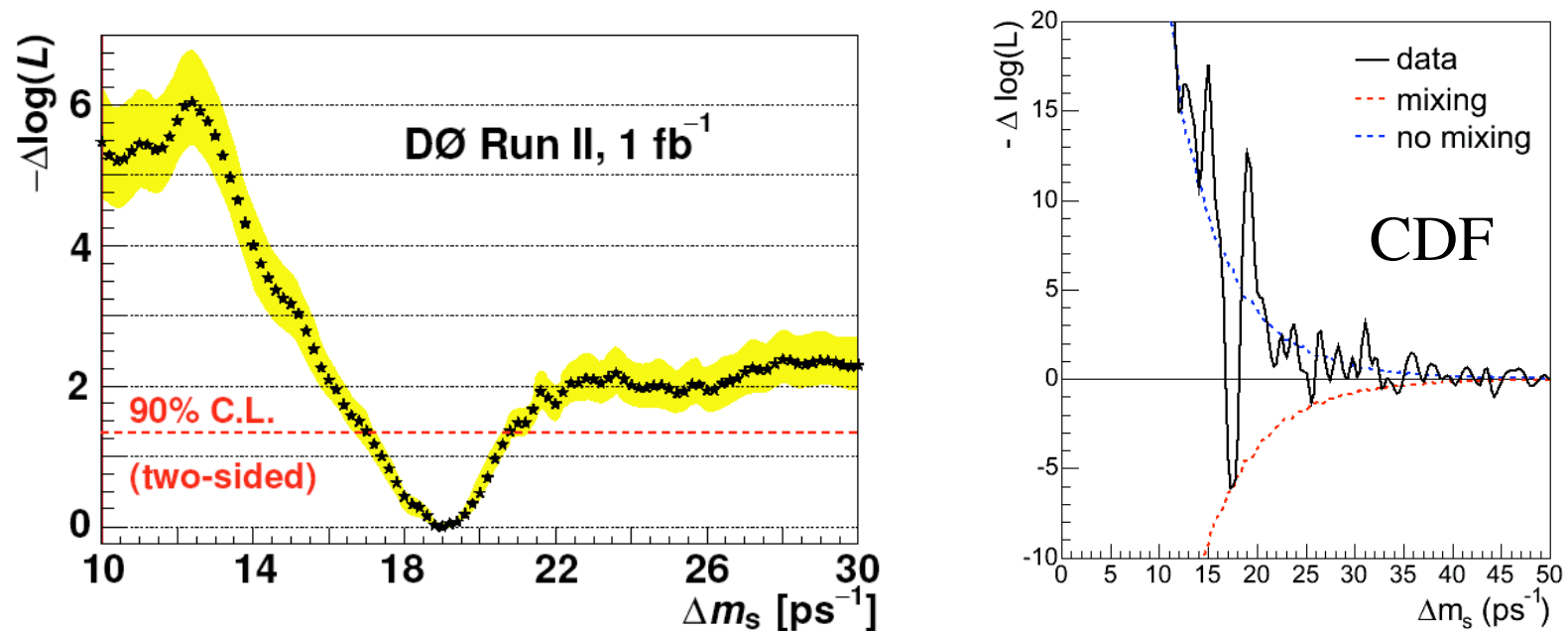


# Combined CDF Amplitude Scan



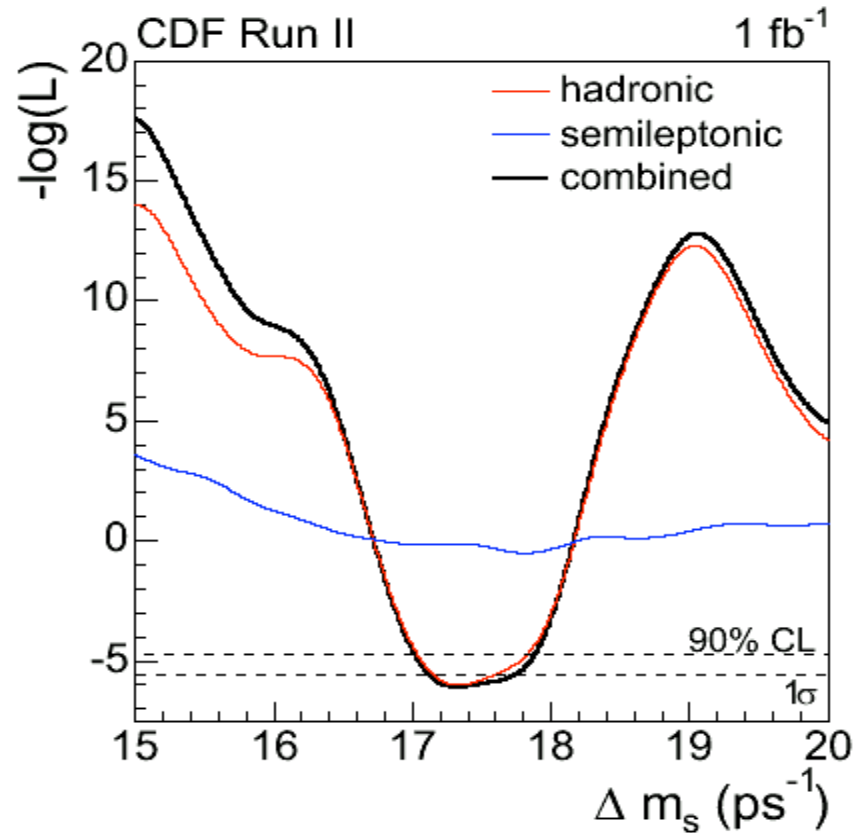
How significant is this result?

# Likelihood



- Likelihood ratio:  $\Delta\log(L) = \log[ L(A=1) / L(A=0) ]$ 
  - likelihood “dip” at signal
- Pseudo-experiments tell us how often this happens randomly:
  - DØ: 5.0 $\pm$ 0.3% within range of 16-22  $\text{ps}^{-1}$
  - CDF: 0.5% anywhere at all
- Result:
  - DØ set 90% CL limit:  $17 < \Delta m_s < 21 \text{ ps}^{-1}$
  - CDF measure:  $\Delta m_s = 17.33^{+0.42}_{-0.21} \text{ (stat)} \pm 0.07 \text{ (syst)} \text{ ps}^{-1}$

# Measurement of $\Delta m_s$



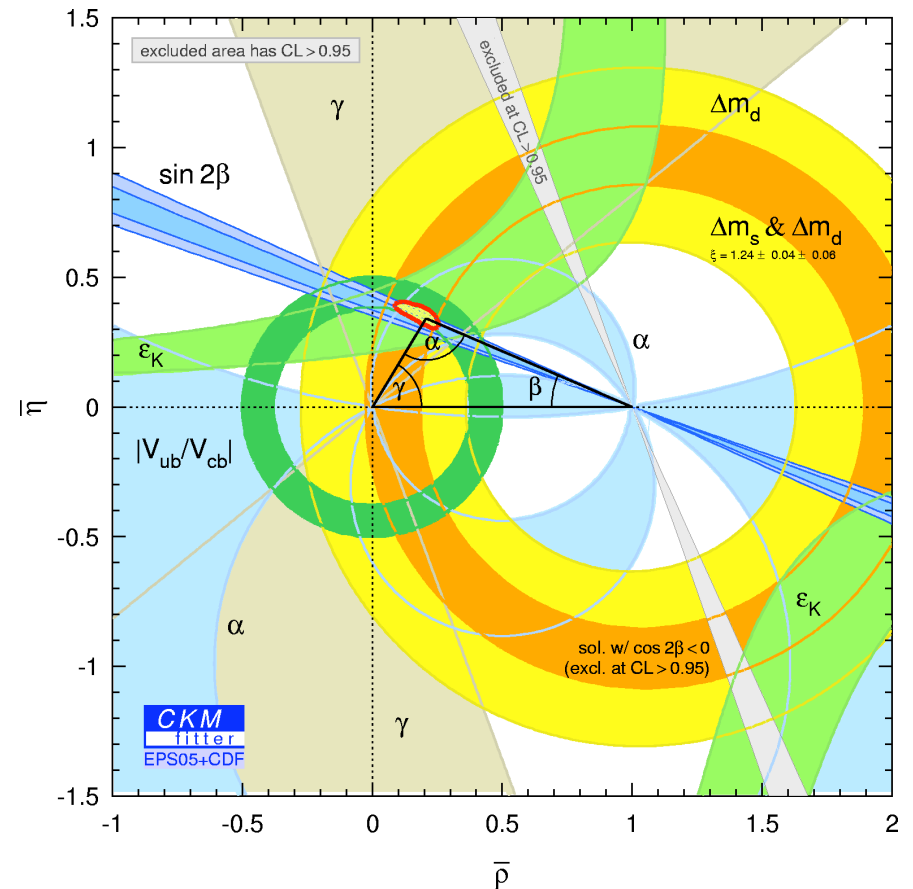
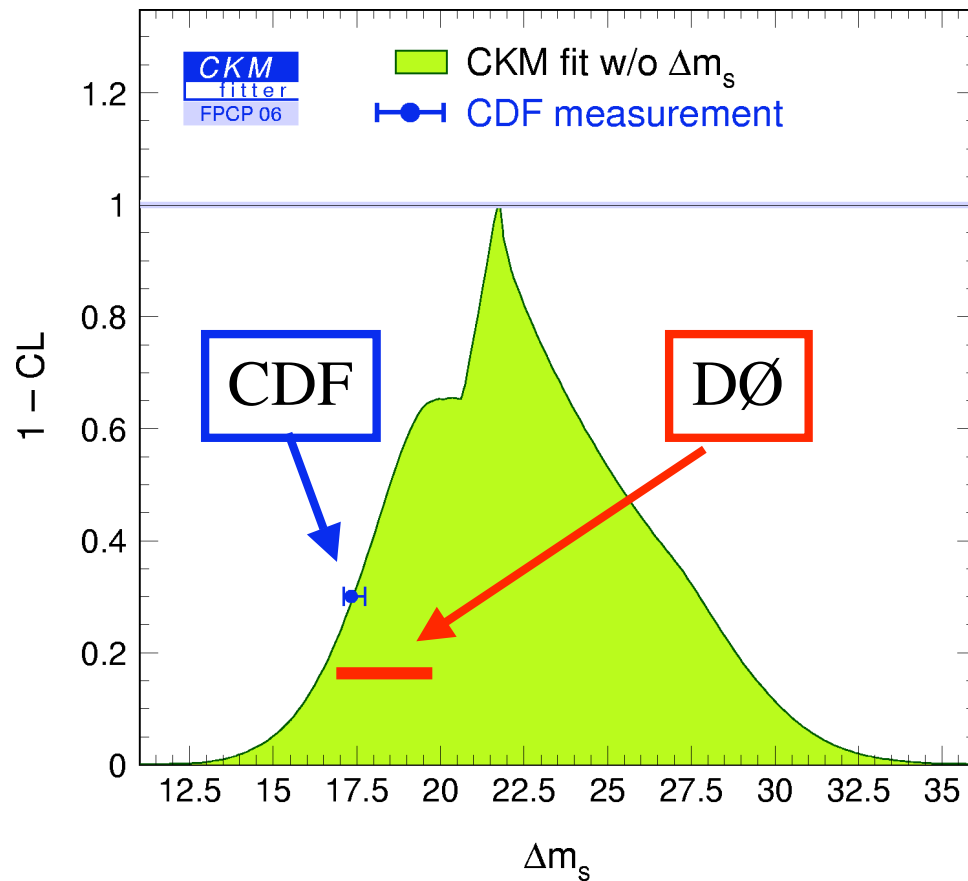
$$\Delta m_s = 17.33^{+0.42}_{-0.21} \text{ (stat)} \pm 0.07 \text{ (syst) ps}^{-1}$$

the measurement is already very precise! ( at 2.5% level )

$\Delta m_s$  in [17.00, 17.91] ps<sup>-1</sup> at 90% CL

$\Delta m_s$  in [16.94, 17.97] ps<sup>-1</sup> at 95% CL

# New Unitarity Triangle Fit



- Significant impact on Unitarity triangle understanding
- So far CKM matrix consistent with Unitarity:  $U^\dagger U = 1$

$$B_s \rightarrow \mu^+ \mu^-$$

# Rare Decay: $B_s \rightarrow \mu^+ \mu^-$

- SM rate heavily suppressed:

$$BR(B_s \rightarrow \mu^+ \mu^-) = (3.5 \pm 0.9) \times 10^{-9}$$

(Buchalla & Buras, Misiak & Urban)

- SUSY rate may be enhanced:

$$BR(B_s \rightarrow \mu^+ \mu^-) \propto \tan^6 \beta / m_A^4$$

(Babu, Kolda: [hep-ph/9909476](#)+ many more)

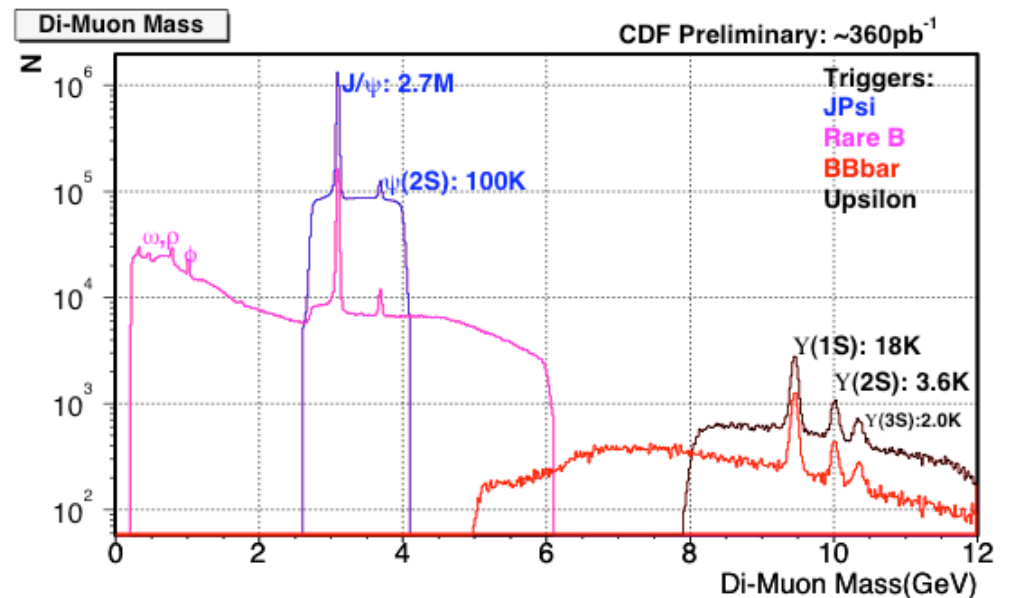
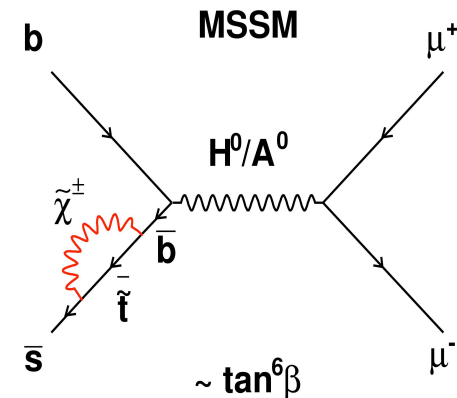
- Key problem:

- Separate signal from huge background\

- Analysis is performed “blind”

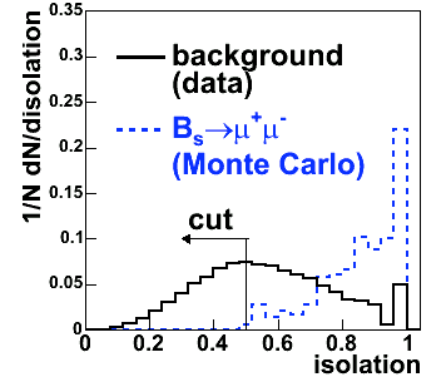
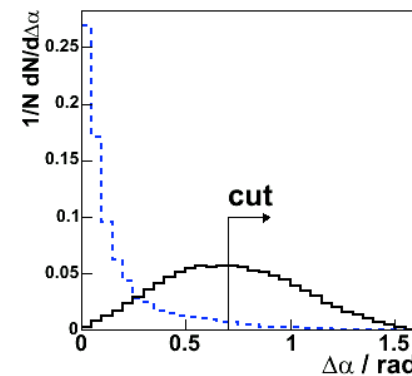
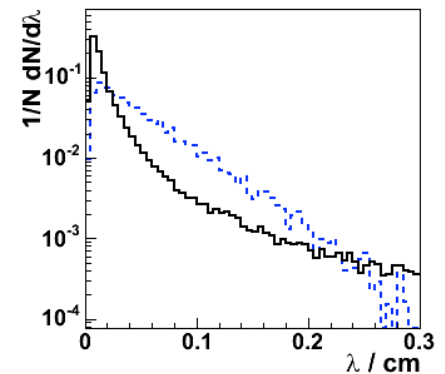
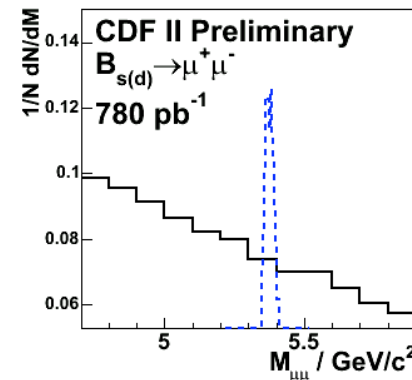
- First finalise cuts and background estimates
- Only then look at data!

- More details on SUSY in lecture tomorrow

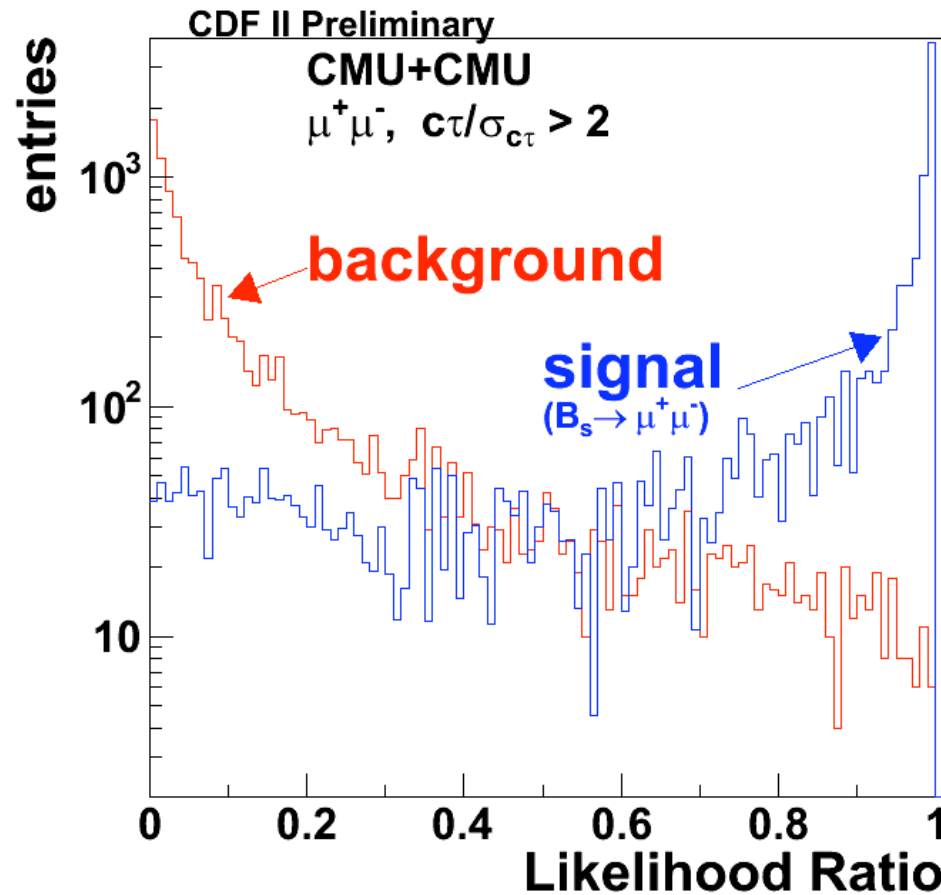


# $B_s \rightarrow \mu^+ \mu^-$ : Cut Optimisation

- Select 80,000 events with
  - 2 muons with  $p_T > 2$  GeV
  - $P_T(\mu\mu) > 6$  GeV
  - $4.669 < M(\mu\mu) < 5.969$  GeV
- Discriminating variables:
  1. Dimuon mass
  2. Lifetime:  $\lambda = ct$
  3. Opening angle between muons:  $\Delta\alpha$
  4. Isolation of  $B_s$
- Construct likelihood ratio using variables 2-4



# $B_s \rightarrow \mu^+ \mu^-$ : Likelihood ratio



- Cut optimised to yield maximal  $\text{Signal}/\sqrt{\text{Bgd}}$ :  $L > 0.99$



# $B_s \rightarrow \mu^+ \mu^-$ : Background Prediction

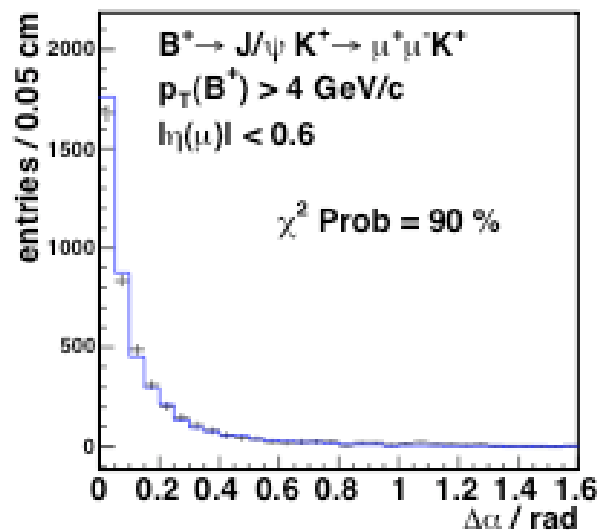
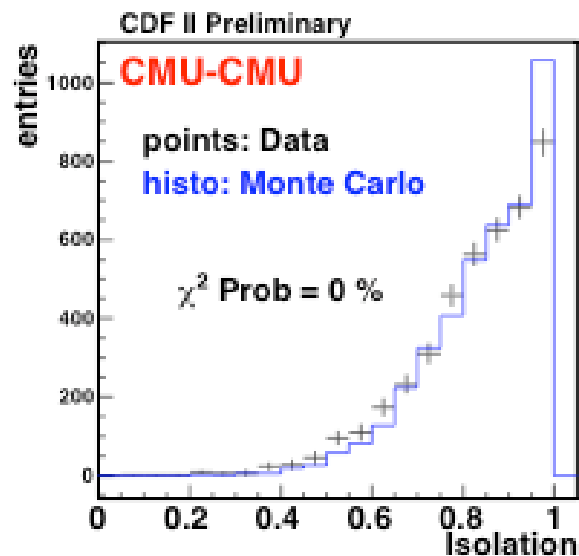
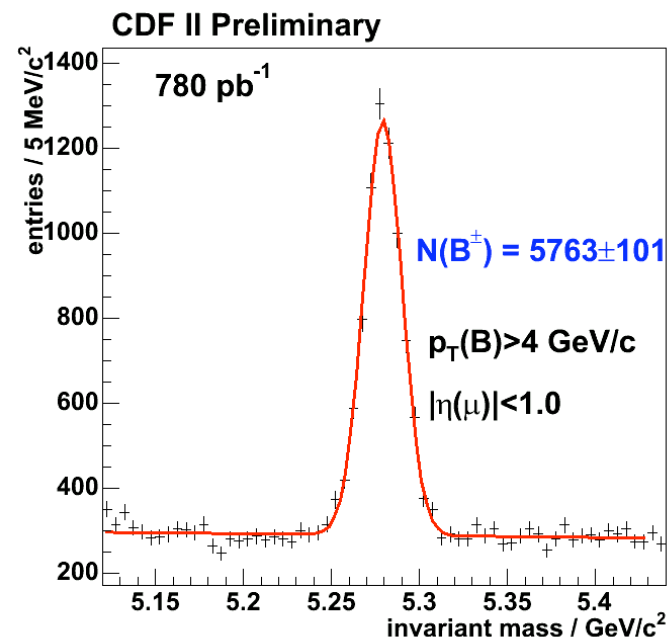
- Background:
  - Random muons from cc and bb
  - QCD jets  $\rightarrow \pi/K \rightarrow \mu + X$
  - Cannot estimate using MC  $\Rightarrow$  use “side bands”
- Define control regions
  - Lifetime < 0 (due to misreconstruction): “**OS-**”
  - Muons with same charge: “**SS**”
  - Fake muons that fail certain ID cuts: “**FM**”

sample $L_R$ cut		CMU-CMU		
		pred	obsv	prob(%)
OS-	> 0.50	$489 \pm (12)$	483	41
	> 0.90	$62 \pm (4)$	73	12
	> 0.99	$4.8 \pm (1.2)$	9	8
SS+	> 0.50	$5.4 \pm (1.3)$	4	40
	> 0.90	< 0.1	0	-
	> 0.99	< 0.1	0	-
SS-	> 0.50	$6.6 \pm (1.4)$	7	49
	> 0.90	$0.6 \pm (0.4)$	1	45
	> 0.99	< 0.1	0	-
FM+	> 0.50	$188 \pm (8)$	159	3
	> 0.90	$34 \pm (3)$	24	7
	> 0.99	$4.5 \pm (1.0)$	9	6

Data agree with background estimates in control regions  
 $\Rightarrow$  Gain confidence in background prediction!

# Signal Acceptance

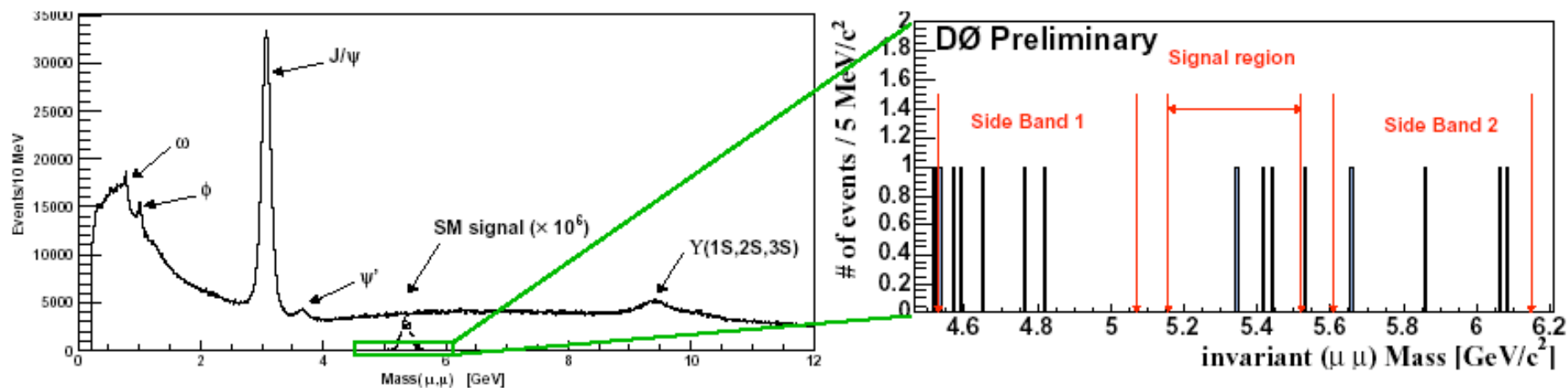
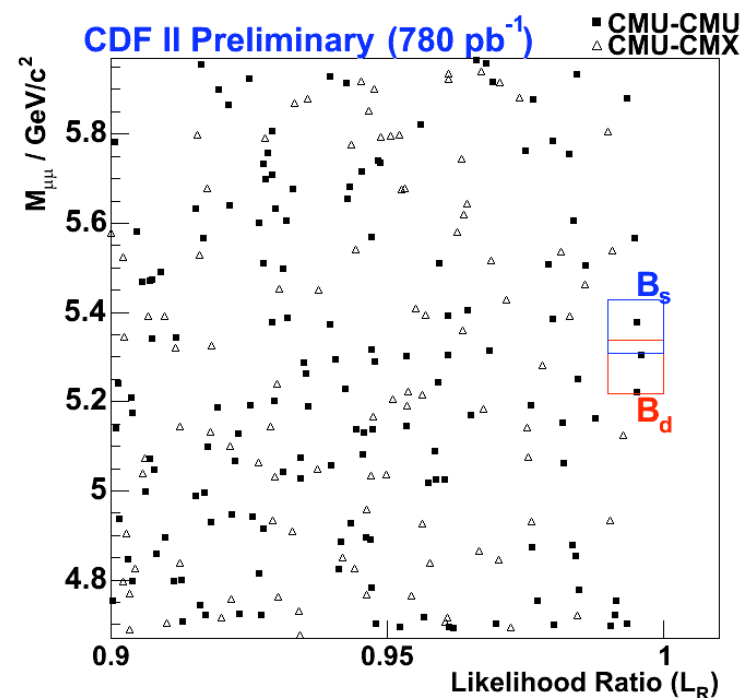
- Does MC reproduce cut variables?
- Use  $B^+ \rightarrow J/\psi + K^+$  as control sample
  - E.g. test isolation cut of  $\text{Iso} > 0.65$
  - MC models data well
    - Disagreements taken as systematic uncertainty



=> Let's open  
the blind box!

# Opening the “Box”: $B_s \rightarrow \mu^+ \mu^-$

	DØ	CDF
Lumi ( $\text{pb}^{-1}$ )	300	780
expected	$3.7 \pm 1.1$	$1.3 \pm 0.4$
observed	4	1

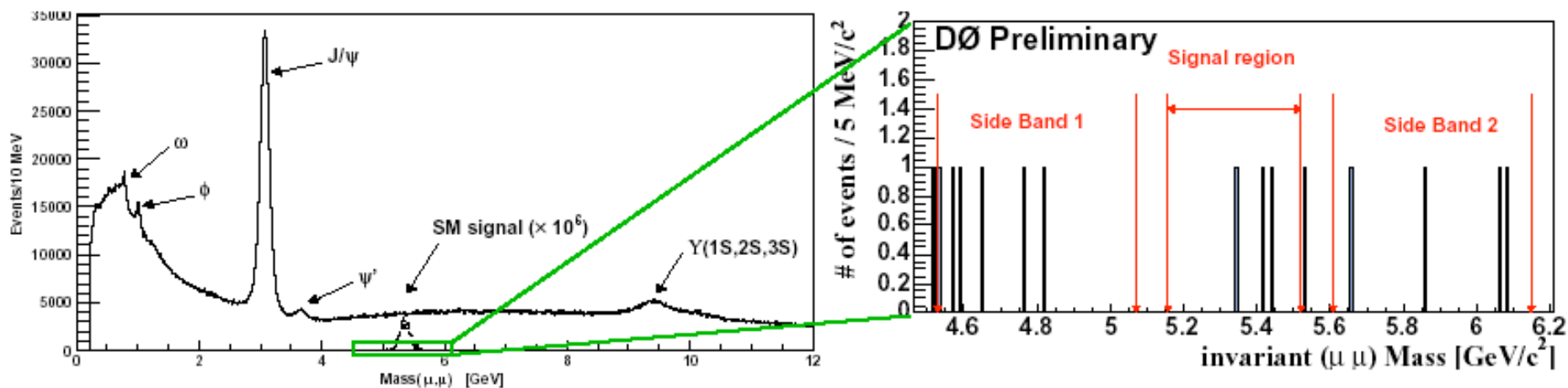
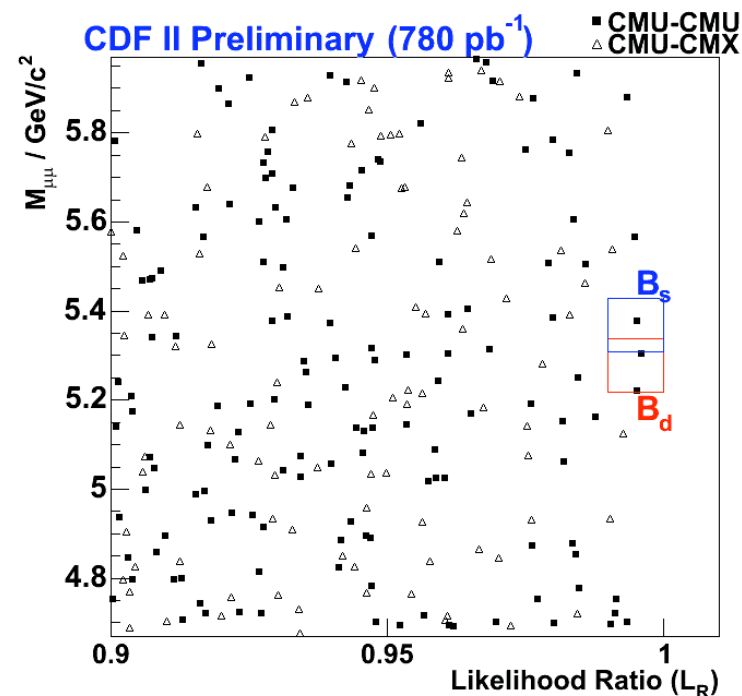


# Calculating a limit

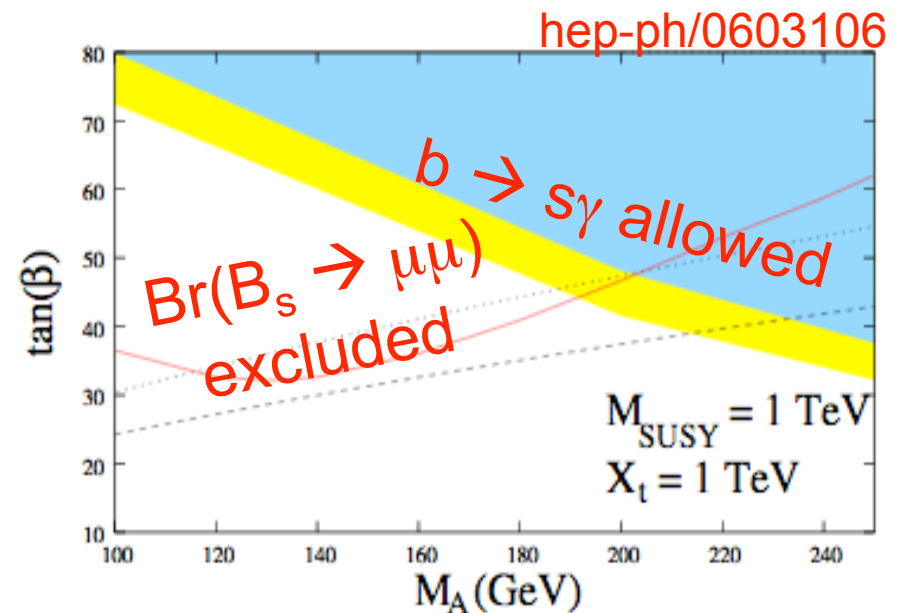
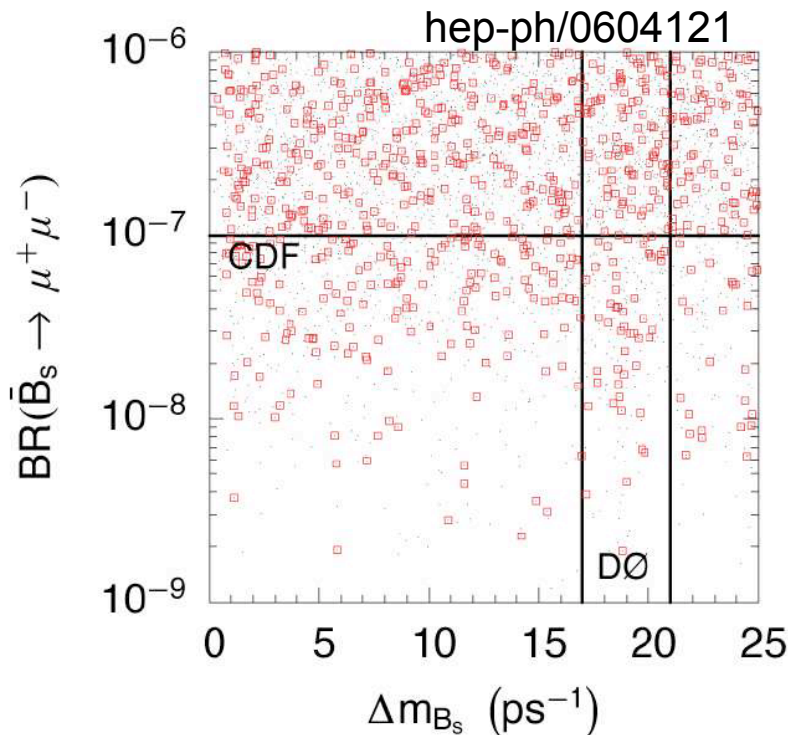
- Different methods:
  - Bayes
  - Frequentist
  - ...
- Source of big arguments amongst statisticians:
  - Different method mean different things
  - Say what YOU have done
  - There is no “right” way
- Treatment of syst. Errors somewhat tricky
- But basically:
  - Calculate probability that data consistent with background + new physics:
    - $P = e^{-\mu} \mu^N / N!$
    - $N$  = observed events
    - parameter  $\mu$  is  $N_{BG} + N_{new}$
    - $P=5\% \Rightarrow$  95% CL upper limit on  $N_{new}$  and thus  $\sigma \times BR = N_{new} / (\alpha L)$
- E.g.:
  - 0 events observed means  $<2.7$  events at 95% C.L.

# Opening the “Box”: $B_s \rightarrow \mu^+ \mu^-$

	DØ	CDF
Lumi (pb <sup>-1</sup> )	300	780
expected	$3.7 \pm 1.1$	$1.3 \pm 0.4$
observed	4	1
BR@95% C.L.	$< 3.7 \times 10^{-7}$	$< 1 \times 10^{-7}$



# What did we learn from B Physics about New Physics?



- SUSY contributions
  - affect both  $B_s$  mixing and  $B_s \rightarrow \mu^+ \mu^-$
  - Strong constraints on SUSY at large  $\tan\beta$  and small  $m_A$

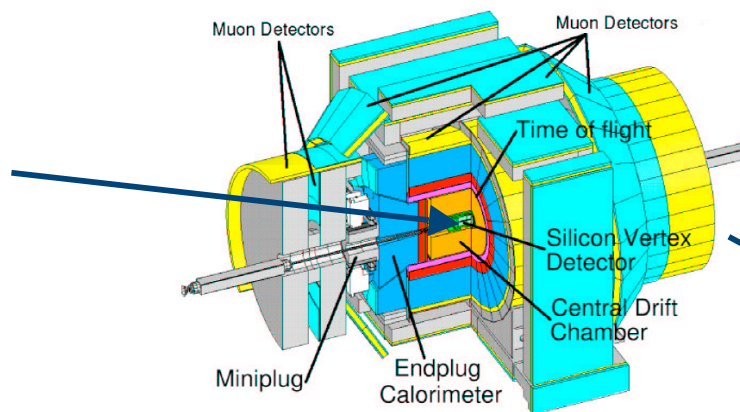
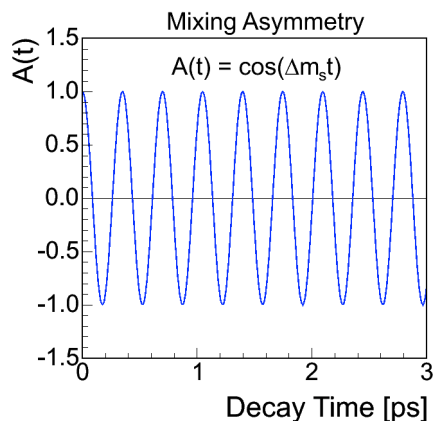
# Conclusions

- New Physics could contribute to B hadron properties:
  - At hadron colliders
    - b-production cross section is 1000 times larger than at the B factories
    - all kinds of B hadrons are produced:  $B_d$ ,  $B_s$ ,  $\Lambda_b$ ,  $B_c$ 
      - The  $\Lambda_b$  lifetime is an interesting topic
  - First evidence of  $B_s$  meson oscillations:
    - Measurement  $\Delta m_s = 17.33^{+0.42}_{-0.21} \text{ (stat)} \pm 0.07 \text{ (syst)} \text{ ps}^{-1}$
  - Search for  $B_s \rightarrow \mu\mu$  yields strong limit
    - sensitive probe of New Physics
- No evidence for new physics contributions (yet)

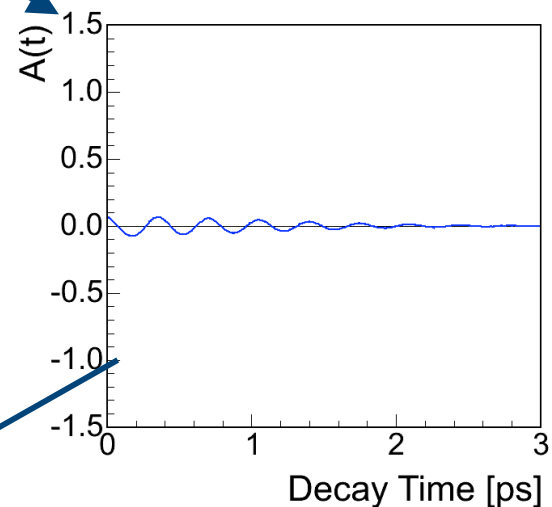
# Backup Slides



# Real Measurement Layout



Data



momentum resolution  
displacement resolution  
flavor tagging power

scan for signal:

$$A(\Delta m_s = 15 \text{ ps}^{-1}) = ?$$

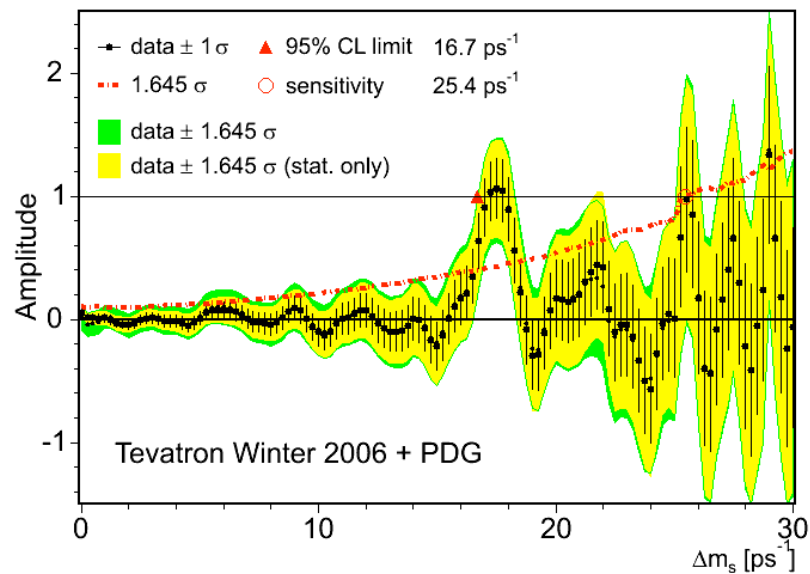
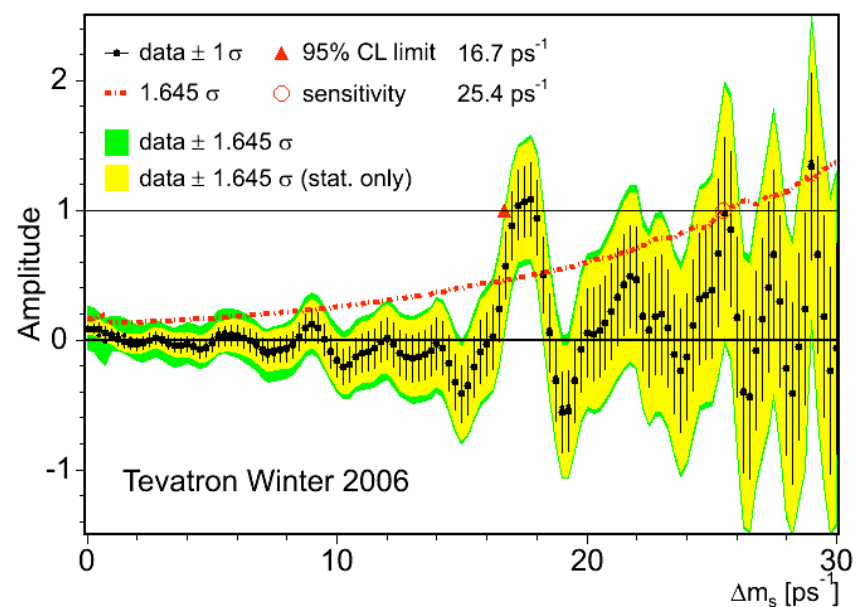
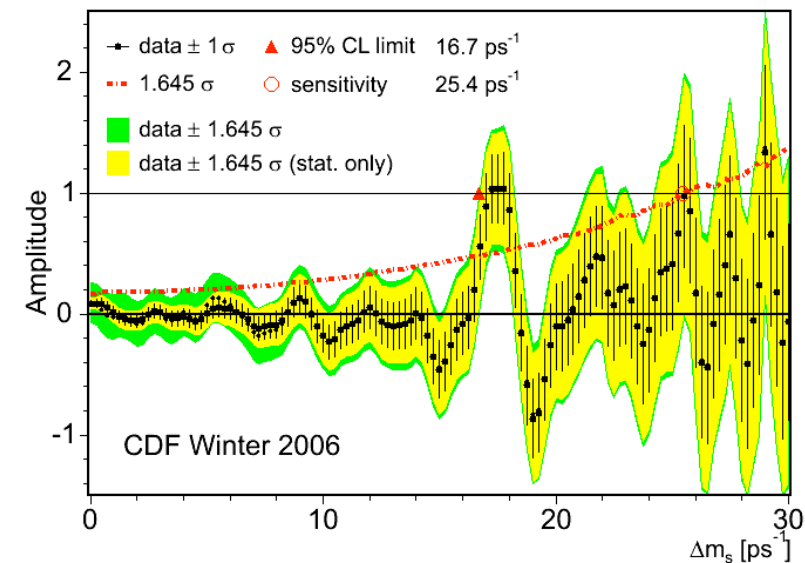
measure frequency:

$$\Delta m_s = ?$$

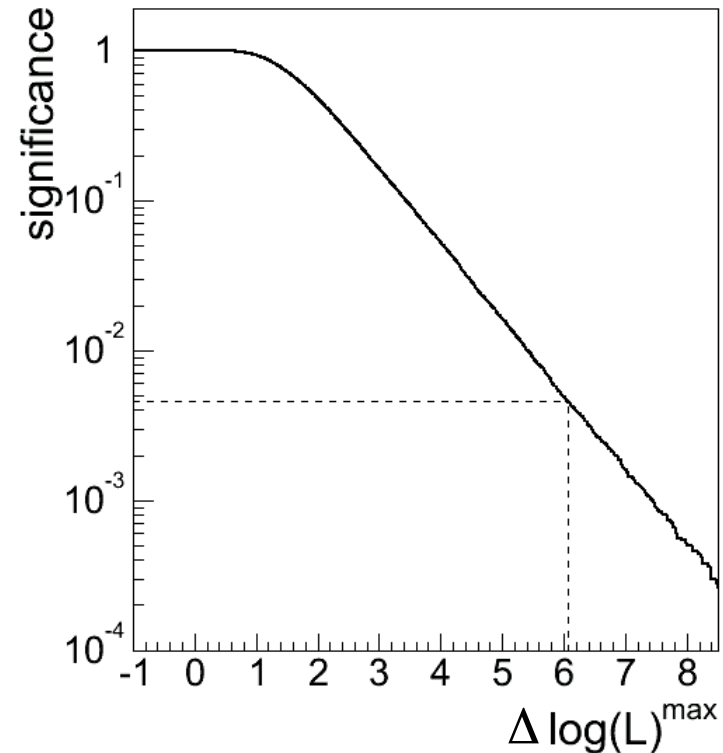
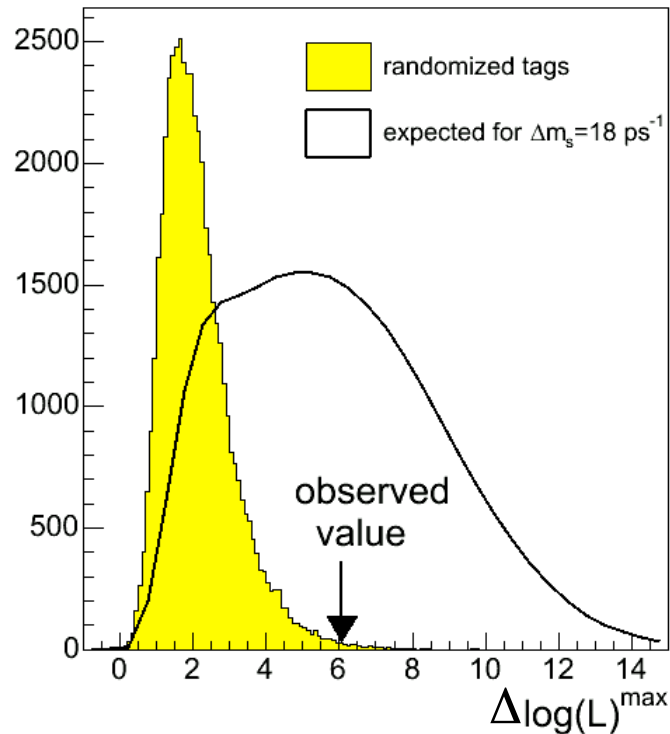
Unbinned  
Likelihood  
Fitter

$$p \sim e^{-t/\tau} [1 \pm AD \cos \Delta m t] \vee R(t)$$

# Combining Tevatron with the World



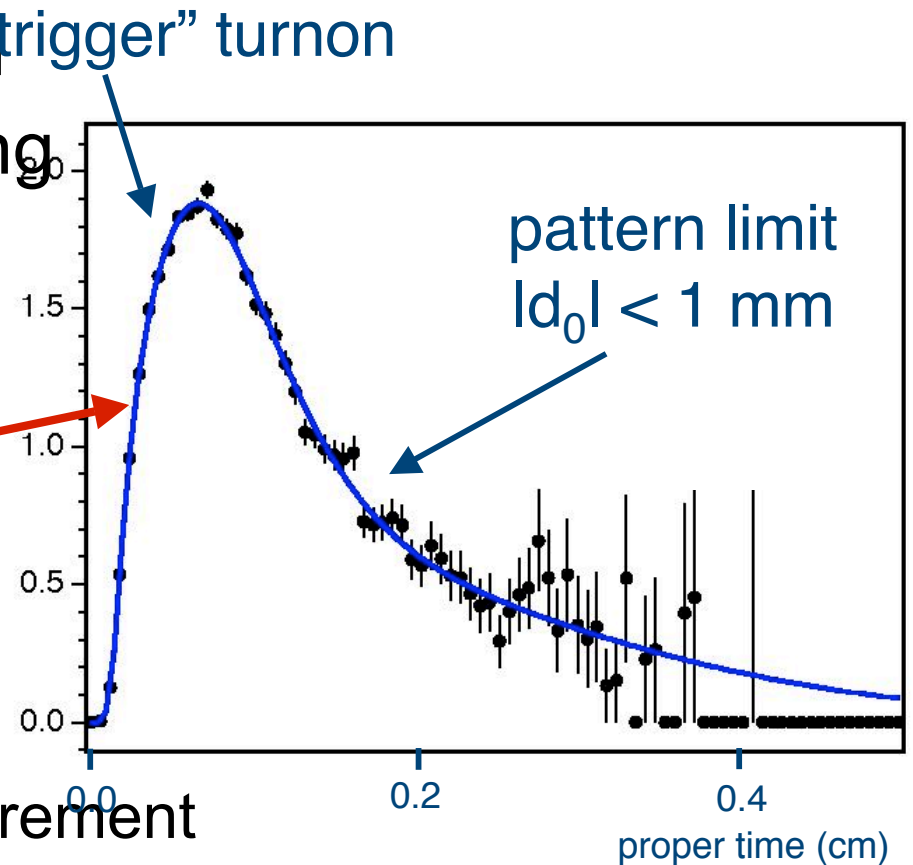
# Likelihood Significance



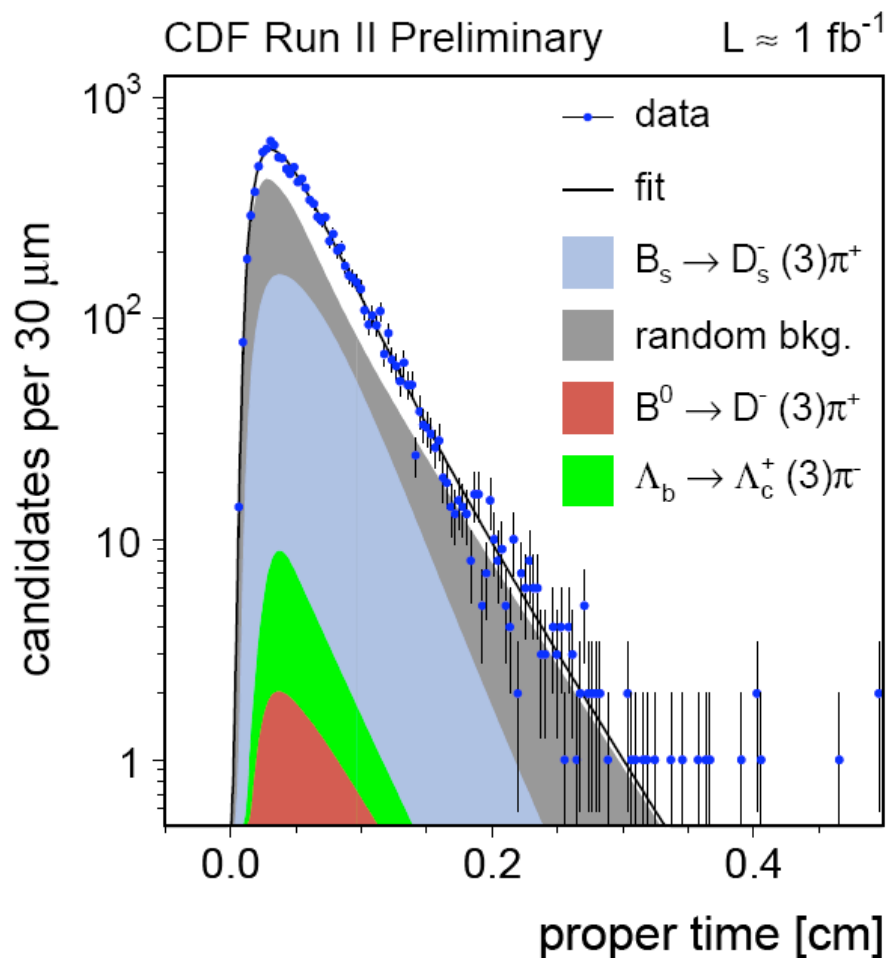
- randomize tags 50 000 times in data, find maximum  $\Delta \log(L)$
- in 228 experiments,  $\Delta \log(L) \geq 6.06$
- probability of fake from random tags = 0.5%  $\rightarrow$  measure  $\Delta m_s$ !

# Hadronic Lifetime Measurement

- SVT trigger, event selection sculpts lifetime distribution
- correct for on average using efficiency function:  
$$p = e^{-t'/\tau} \bigvee R(t',t) \cdot \epsilon(t)$$
- efficiency function shape contributions:
  - event selection, trigger
- details of efficiency curve
  - important for lifetime measurement
  - inconsequential for mixing measurement



# Hadronic Lifetime Results



Mode	Lifetime [ps] (stat. only)
$B^0 \rightarrow D^- \pi^+$	$1.508 \pm 0.017$
$B^- \rightarrow D^0 \pi^-$	$1.638 \pm 0.017$
$B_s \rightarrow D_s \pi(\pi\pi)$	$1.538 \pm 0.040$

$\lambda$  World Average:

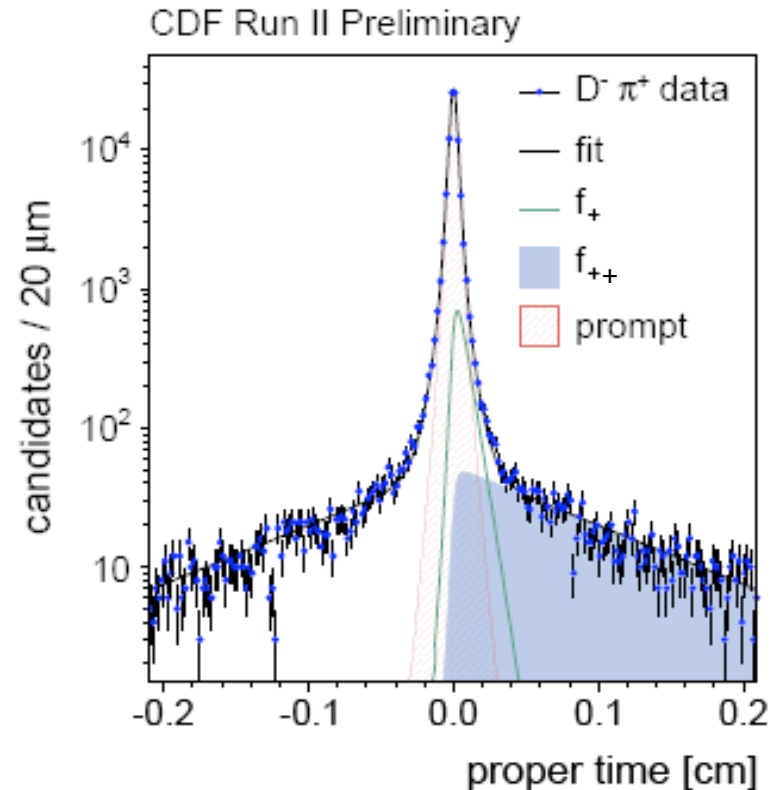
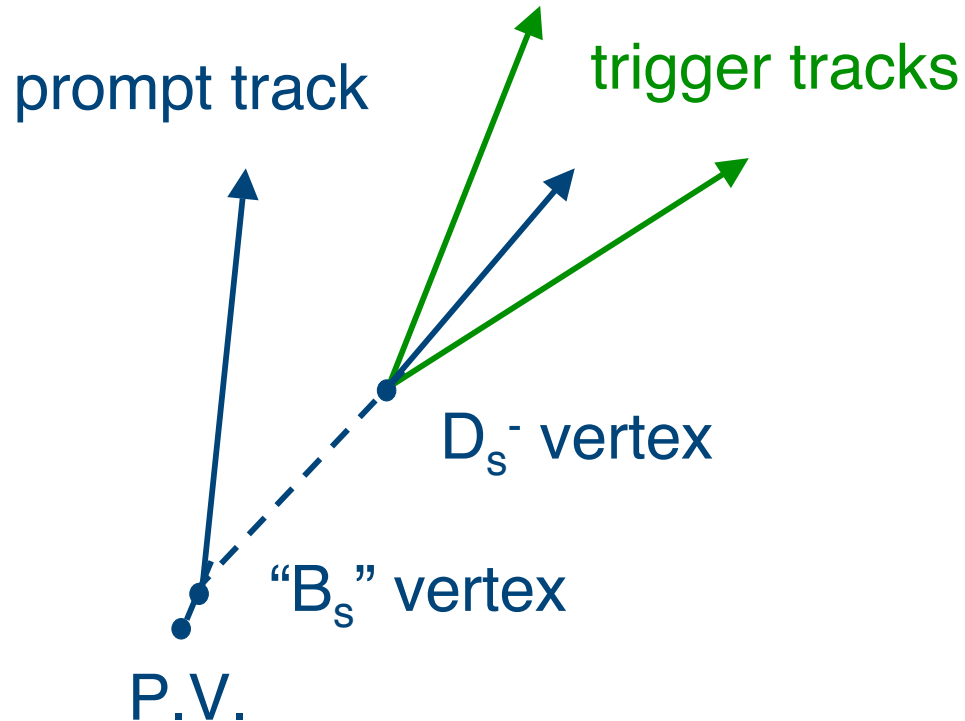
$$B^0 \rightarrow 1.534 \pm 0.013 \text{ ps}^{-1}$$

$$B^+ \rightarrow 1.653 \pm 0.014 \text{ ps}^{-1}$$

$$B_s \rightarrow 1.469 \pm 0.059 \text{ ps}^{-1}$$

Excellent agreement!

# Calibrating the Proper Time Resolution



- utilize large prompt charm cross section
- construct "B<sup>0</sup>-like" topologies of prompt D<sup>-</sup> + prompt track
- calibrate ct resolution by fitting for "lifetime" of "B<sup>0</sup>-like" objects